

CONVERSION OF CONTINUOUS-TONE
IMAGES INTO BILEVEL REPRESENTATION
APPLIED TO A COLOR IMAGE SCANNER
AND A COLOR INK JET PLOTTER

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ABSTRACT

The implementation and evaluation of a pseudo-gray scale algorithm in a color image scanner is presented. The scanner is especially developed to be compatible with a bilevel ink jet color plotter. Thus, the algorithm converts a continuous-tone color image into a bilevel color representation, that can be plotted directly on the ink jet color plotter.

After a general introduction and a review of a few existing pseudo-gray scale algorithms, the report centers on two non-adaptive algorithms: the ordered dither and the digital halftone algorithm. Both use a matrix of position-dependent thresholds. The arrangement of thresholds in the matrix is the only difference between the two algorithms. The bilevel pseudo-gray scale is obtained by comparing each picture element in the original image with its corresponding position in the threshold matrix. This yields the decision to plot an ink dot or not.

The algorithms are implemented using a combined hardware and software solution. It is shown how the thresholds in the matrix can be changed to linearize the scanner/plotter system and to provide lightness and contrast control of the reproduced image. Also, two different threshold matrix sizes are evaluated: a 4×4 and an 8×8 threshold matrix.

Finally, a short introduction to the theory of ink color reproduction is given, followed by a presentation and discussion of color errors in the scanner/plotter system. A few color images produced by the system are presented.

The use of images in computer applications ranging from digital image processing and computer graphics to electronic facsimile has grown very fast. This has also increased the demand for hardcopy output devices, which can produce good reproductions of continuous-tone images both in black-and-white and in color. The recording could be made on paper, film or any other permanent medium.

Top of the line among the existing color hard-copy devices are special purpose cameras. Most of them convert the videosegment from a raster scan graphic display or any other CRT to an image represented by a film negative, polaroid print or color slide. The use of a photographic recording medium will often produce an excellent reproduction, as the density at each point on the film can be varied as a function of the corresponding picture element (pixel) intensity. Examples are the Dunn Color Camera from Dunn Instruments, the desk-top Color Camera from Image Resource Corp. and a color copier on instant film from Matrix Corp. Their main disadvantages are a high price per copy and the small size copies.

However, the output of most hard-copy devices is in binary form. This is often due to the printing process used in the device and to constraints on cost and complexity. Electrostatic plotters, thermal plotters, microfilm recorders, dot-matrix plotters and ink jet plotters all belong to this category. Commercially available binary hard-copy devices, that can also produce color copies are e.g. the Trilog dot matrix printer (Trilog, Inc.) and the Printa Color and the Applicon, Inc. (CP5586) ink jet plotters. The binary nature of the devices implies that a recording can be divided into a large number of discrete small areas, here called display dots, that can take on only one of two possible states, referred to as on and off. The size of the display dots depends entirely on the resolution of the hard-copy device.

The reproduction of a continuous-tone image on a binary hard-copy device cannot be achieved straightforwardly. Instead, one has to find methods to simulate gray scales. This can be done by modulating the spatial

density of the display dots to produce a so-called pseudo-gray scale rendition of the continuous-tone image, thus relying on the viewer's inability to resolve all the details of the binary image, resulting in local averaging. Principally one tries to achieve a maximum gray scale resolution within the smallest possible area of the reproduction. Such pseudo-gray scale techniques have received considerable attention in the literature (Knowlton et al. 1972, Bayer 1973, Judice et al. 1974, Gard 1976, and Jarvis et al. 1976b).

Basically the techniques can be divided into two groups of strategies:

I. One strategy is used when the number of display dots is much greater than the number of samples of the continuous-tone image. This implies the use of mapping techniques, i.e. each pixel is associated with a cluster of bilevel display dots, as in Figure 1.1. This is roughly analogous to the halftone screening process used in the printing industry, although that process is based on variations in size of the reproduced dot (cf. Figure 1.2). If the spatial resolution of the continuous-tone image is to be preserved and severe contouring avoided, the mapping techniques require a ratio of pixels to display dots larger than 1:16. A variety of mapping techniques exists in the literature. The survey papers of Knowlton et al. (1972) and Gard (1976) cover some of these variations.

II. Another basic strategy must be used when the number of display dots is equal to the number of pixel elements of the continuous-tone image. As one pixel corresponds to one and only one display dot, a decision must be made whether this dot should be on or off. Principally this is done by using threshold techniques (cf. Figure 1:3). A number of algorithms have been described that create patterns of on and off dots that preserve detail and average brightness over extended areas. A summary of some of these techniques can be found in the survey paper by Jarvis et al. (1976b).

This report describes the selection and implementation of pseudo-gray scale algorithm in a color image drum scanner (Nilsson et al. 1981). The scanner is especially developed to be directly compatible with an already existing ink jet color plotter (Hertz et al. 1976, Bladh et al.

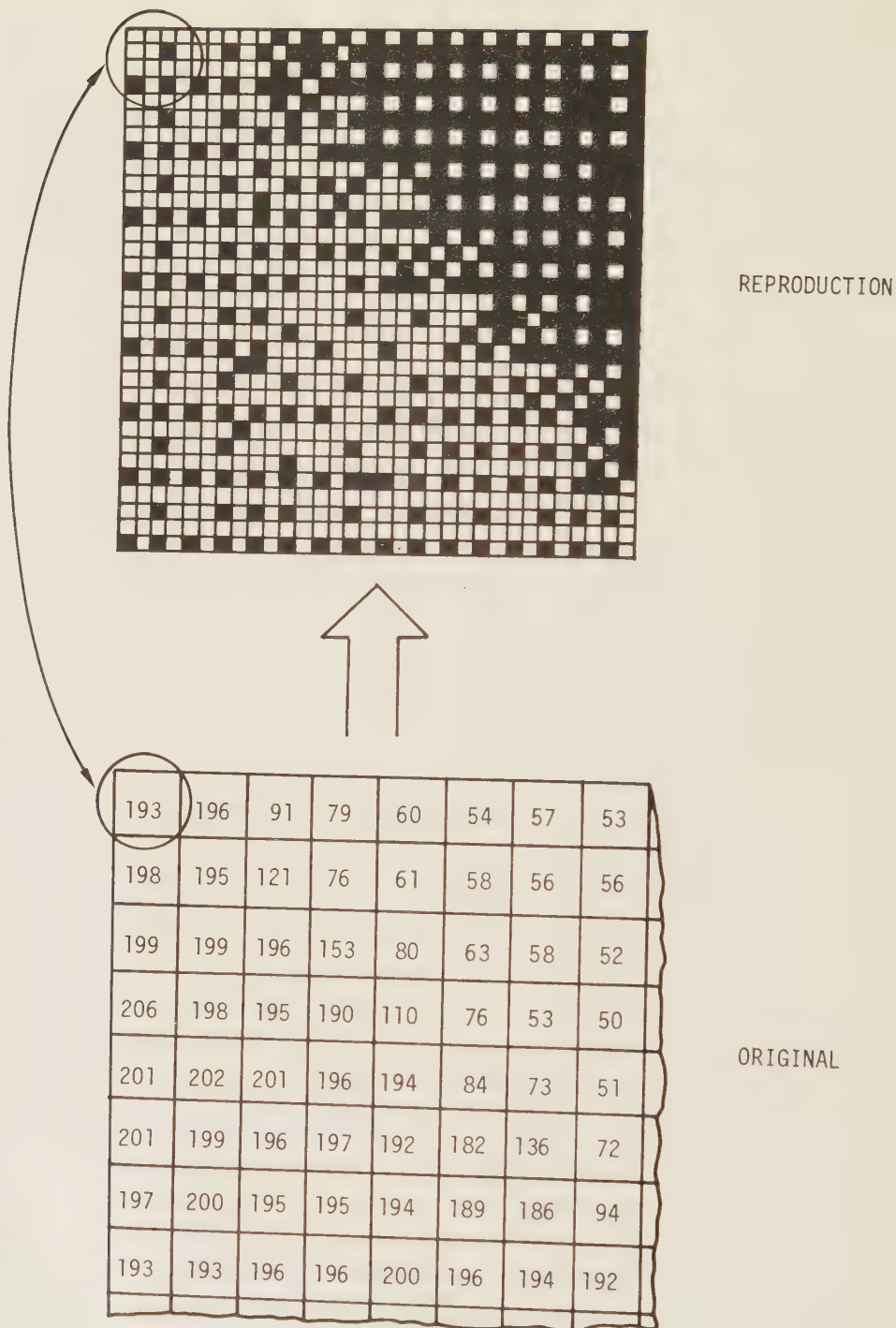


Figure 1.1. Mapping techniques. One pixel value is mapped into a cluster of bilevel display dots. In this example a square of 16 display dots is shown.

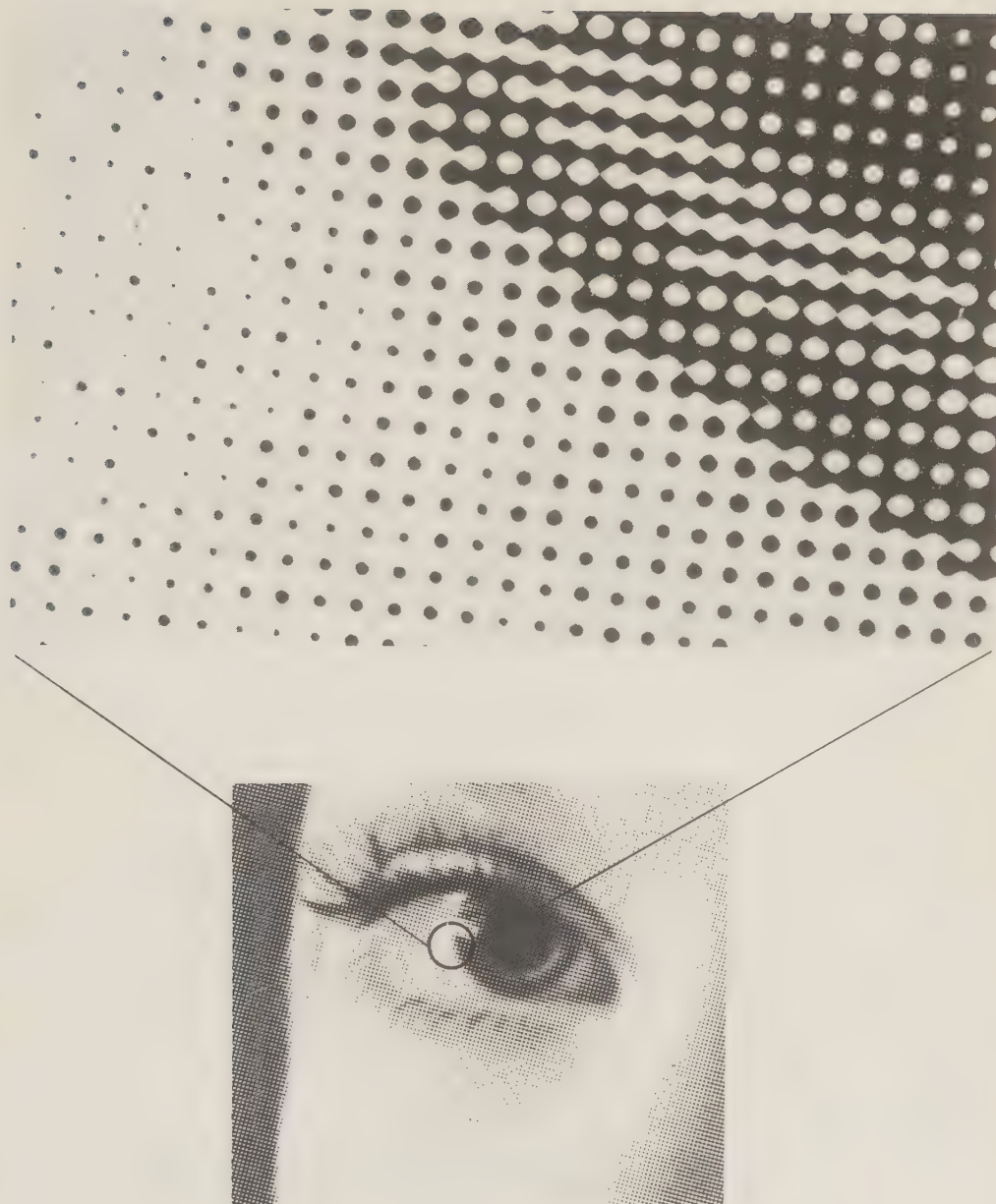


Figure 1.2. An example of the halftone screening process, used in the printing industry. The process is based on variations in the size of the reproduced dots. This is clearly visible in the magnified view of a small area in the print.

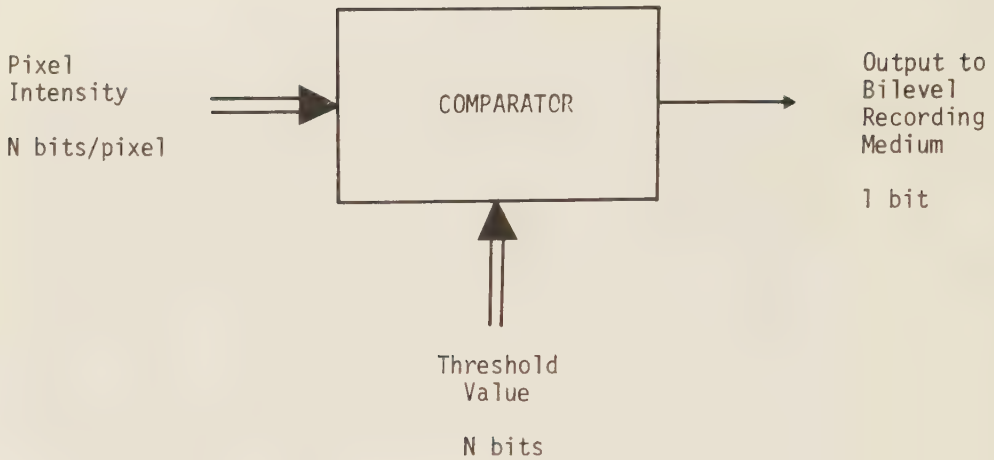


Figure 1.3. Threshold technique principle. The pixel intensity (n bits) is compared to a threshold (n bits). The comparator generates a one bit value, depending on the outcome of the comparison.

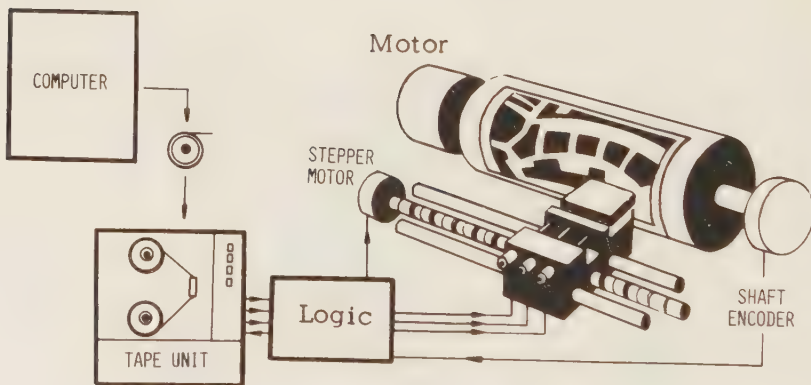


Figure 1.4. Basic units of the color plotter. The information to be plotted is computed in a suitable format by a computer and stored on a magnetic tape. This tape is then read by a magnetic tape unit into a buffer memory. The read-in and read-out periods of the memory are governed by control circuits, and the read-out signals are used to modulate the intensity of the three ink jets (magenta, yellow, and cyan) mounted in front of the rotating drum carrying the recording paper.

1979). The mechanical construction of the scanner resembles the plotter but has the recording head replaced by an optical scanner head (Nilsson 1981).

The ink jet color plotter is a drum plotter and it consists of four different units, shown in Figure 1.4: the plotting unit, a magnetic tape transport, a buffer memory, and a control unit. The plotting unit consists of a recording head with three electronically controlled ink jets plotting the colors magenta, yellow, and cyan. As the drum is rotating (normally at a surface speed of 4 m/s), a lead screw moves the recording head in 0.2 mm increments parallel to the drum. This gives a recording line density of 5 lines/mm. A shaft encoder mounted on the drum provides the same resolution along each recording line. Thus the plot will contain $0.2 \times 0.2 \text{ mm}^2$ plotted dots. A maximum plotting area of $615 \times 665 \text{ mm}^2$ results in a maximum of $3075 \times 3325 \times 3 > 30.6$ million plotted dots.

The pseudo-gray scale algorithm used in the scanner directly converts a continuous-tone color image represented by 8 bits/pixel/color into a bi-level color representation before storage. This not only reduces the required data storage 1:8 for each of the three colors, it also results in an image that can be directly plotted on the bilevel ink jet color plotter.

Because of compatibility requirements the scanner is designed to have the same scanning line density as the plotter, being 5 lines/mm. From this follows that the pseudo-gray scale algorithm must use a threshold technique. In the following we will discuss the selection of a suitable algorithm for our purpose and describe in detail the hardware implementation. In another section it will be shown how modifications of threshold values are used for the correction of scanner and plotter non-linearities. Finally, we will discuss limitations and refinements.

2 A REVIEW OF PSEUDO-GRAY SCALE ALGORITHMS

2.1 Terminology

Figure 1.3 illustrates the basic strategy of a threshold algorithm used to present a continuous-tone image, in the following called source image, on a bilevel recording medium. The source image is scanned by a scanning head, line by line, and the output signal is sampled along each line. This divides the source image into picture elements (pixels). A multibit signal (8-bits in our application) representing each pixel intensity is compared with a threshold signal. When the source image intensity is less than or equal to the threshold, the corresponding display dot is turned on, otherwise the display dot is remaining off. This corresponds to the presence or absence of an ink dot in the copy, when an ink jet plotter is used. The white and black are reversed compared to what is used in most of the papers referred to. Most of these papers use plasma displays or CRT screens where "on" represents high intensity and "off" represents a black screen or display. We have converted the results from those papers to follow the convention of this paper, i.e. to apply to ink on paper.

2.2 Adaptive and non-adaptive algorithms

2.2.1 Introduction

The ability of a threshold algorithm to accurately reproduce a continuous-tone image depends, of course, on the selection of thresholds. E.g. a single fixed threshold used for the entire image would only result in a reproduction consisting of featureless light and dark area bands which bear only an outline resemblance to the original (cf. Figure 2.1).

A slight improvement would be to replace the fixed threshold by equally distributed random numbers over the quantization range with a new random number generated for each pixel in the entire image. The resulting image would then show obvious tonal variations but suffer from large amounts of noise and a poor resolution (Jarvis et al. 1976b). This is due to the fact that the display dot resolution is insufficient to ensure a uniform distribution of thresholds within a small enough local region of the image.



a



b

Figure 2.1. The result from a single threshold algorithm, shown in (b). The original continuous-tone image is shown in (a). The threshold was set to 128 in an 0-255 quantization range.

The picture quality can be improved by using a periodic-random algorithm where N thresholds are arranged in a n -by- n matrix ($n^2 = N$) and repeated in a doubly periodic, checkerboard fashion over the entire source image. This ensures that the number of dots present within each $n \times n$ region of the recording is very nearly proportional to the average intensity of the source image. The main disadvantage here is that the boundaries between regions encompassed by each matrix are clearly visible, as shown in Figure 2.2.

Many algorithms that produce much better results than this have been devised and they can broadly be classified as being either adaptive or non-adaptive.

2.2.2 Adaptive algorithms

The adaptive algorithms generate thresholds as a function of the image itself (cf. Figure 2.3). Often the thresholds are calculated based on the neighborhood pixel values.

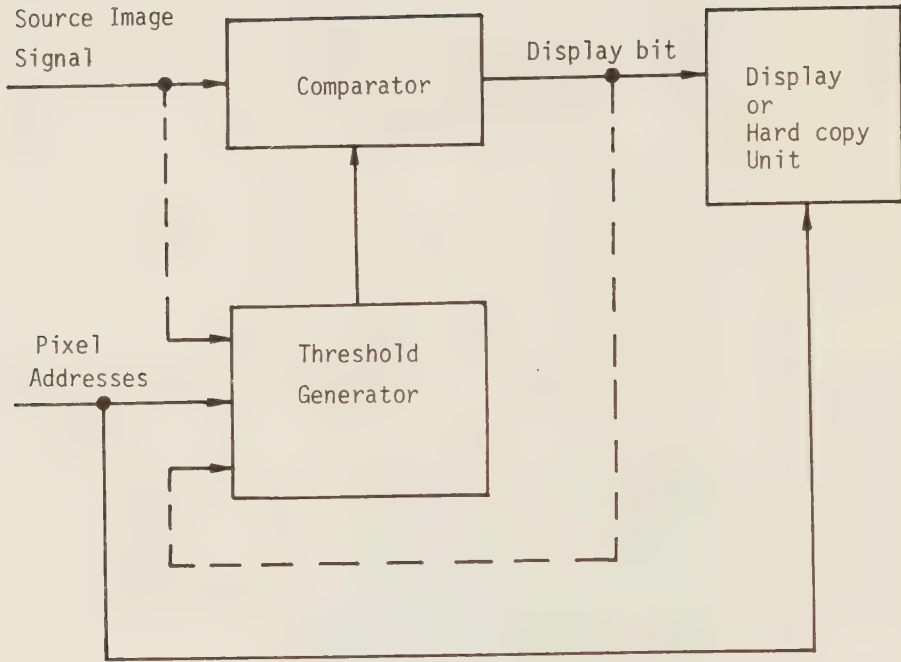
The constrained average technique (Jarvis et al. 1976a) assigns a threshold to each pixel of the source image as a function of the average of the pixel itself and its eight surrounding neighbors. The algorithm also incorporates edge emphasis to increase the legibility of textual information and other areas of high detail. The threshold, T_{xy} , is calculated from the equation

$$T_{xy} = A_{xy} + \gamma \left(1 - \frac{A_{xy}}{I_{\max}} \right) \quad (1)$$

where γ is a so-called "constraining factor". $I_{\max}$ is the maximum intensity and A_{xy} is the local average over the eight surrounding neighbors. The parameter γ controls the apparent contrast of the reproduction and must be nonzero, a typical range being $0.04 I_{\max} - 0.06 I_{\max}$. Eq. (1) indicates that the threshold assigned by the algorithm comprises the local average adjusted by an amount which itself is a function of the local average. The adjustment is positive for $A_{xy} < \frac{I_{\max}}{2}$ zero for $A_{xy} = \frac{I_{\max}}{2}$ and negative for $A_{xy} > \frac{I_{\max}}{2}$. The magnitude of the adjustment increases



Figure 2.2. A bilevel reproduction generated by using a periodic-random algorithm, where 16 random thresholds are arranged in a 4×4 matrix. The threshold matrix is repeated over the entire source image. The reproduction contains clearly visible boundaries which are introduced by the threshold matrix.



—— All Algorithms

- - - Adaptive Algorithms

Figure 2.3. The principle of adaptive algorithms. The thresholds are generated as a function of the image itself.

as A_{xy} moves away from $\frac{I_{\max}}{2}$.

Another adaptive algorithm suggested by Morrin (1974) combines edge emphasis with a dynamic threshold. At each pixel a decision is made whether or not the pixel intensity lies above or below two fixed thresholds:

$$\begin{array}{ll} \text{If } I_{xy} > T_{\max} & \text{then off} \\ \text{If } I_{xy} < T_{\min} & \text{then on} \end{array} \quad (2)$$

If neither condition is met, i.e. $T_{\min} \leq I_{xy} \leq T_{\max}$, the following algorithm is employed. A neighborhood average A_{av} is computed by averaging the current pixel value with the value of the previous pixel. The algorithm also uses the intensities of the current pixel I_{xy} , the previous pixel $I_{x,y-1}$ and the adjacent pixel of the previous line $I_{x-1,y}$ to calculate a composite difference D_c :

$$D_c = \frac{I_{xy} - I_{x-1,y}}{2} + \frac{I_{xy} - I_{x,y-1}}{2} \quad (3)$$

Finally the decision is made

$$\text{If } I_{xy} > mD_c + \alpha A_{av} \quad \text{then off} \quad (4)$$

The quantity m is an edge emphasis sensitivity factor and α is used to bias the decision toward the white region.

A more sophisticated algorithm which provides error minimization in two dimensions is the minimized average error algorithm (Jarvis et al. 1976b). In this algorithm all thresholds are initialized to the same value, such as $\frac{I_{\max}}{2}$. When each pixel is compared to its threshold and the on/off decision is made, the decision error is computed. The calculated error is then used to modify the thresholds of the neighboring pixels for which an on/off decision has not yet been made.

2.2.3 Non-adaptive algorithms

Non-adaptive algorithms all rely on the fact that pixels in a particular region of the continuous-tone image usually have intensities which are

relatively close to one another. Thus by using a predetermined matrix as thresholds which are distributed across the quantization range, one ensures that over the area encompassed by the matrix. The resulting combination of display dots corresponds to the local intensity of the continuous-tone source image. Then the thresholds only depend on the spatial position of the pixels and are completely independent of pixel intensities.

Using a $n \times n$ matrix, D_{ij}^N , with $n^2 = N$ thresholds, the on or off decision is made from

$$\text{If } I_{xy} \leq D_{ij}^N \quad \text{then on} \quad (5)$$

$$\quad \quad \quad \text{else off}$$

where $i = x \text{ modulo } n$

$j = y \text{ modulo } n$

Thus the same matrix is repeated over the entire source image (cf. Figure 2.4). The arrangement of the thresholds in the matrix is the only difference between the algorithms. Two non-adaptive algorithms will be described in detail: The ordered dither algorithm and the digital half-tone algorithm.

2.2.4 The ordered dither algorithm

Historically, ordered dither was first proposed by Limb (1969) as a means of reducing contouring in TV-images reproduced by a limited number of intensity levels. He used dither patterns determined from evaluations of visual models, confirmed by subjective tests. Lippel et al. (1971) later applied this technique to bilevel representation of continuous-tone images in a pulse code modulation (PCM) transmitter/receiver system. Bayer (1973) derived a set of conditions that the dot patterns must meet to minimize unwanted texture in the reproduction of an image with low detail and relatively constant brightness. Judice et al. (1974) found a simple recursion relationship between the 2×2 matrix proposed by Limb and the matrices generated by Bayer.

The crucial difference between ordered dither and other threshold techniques is the spatial arrangement of the thresholds within the matrix. Ordered dither specifies that the average distance between numerically

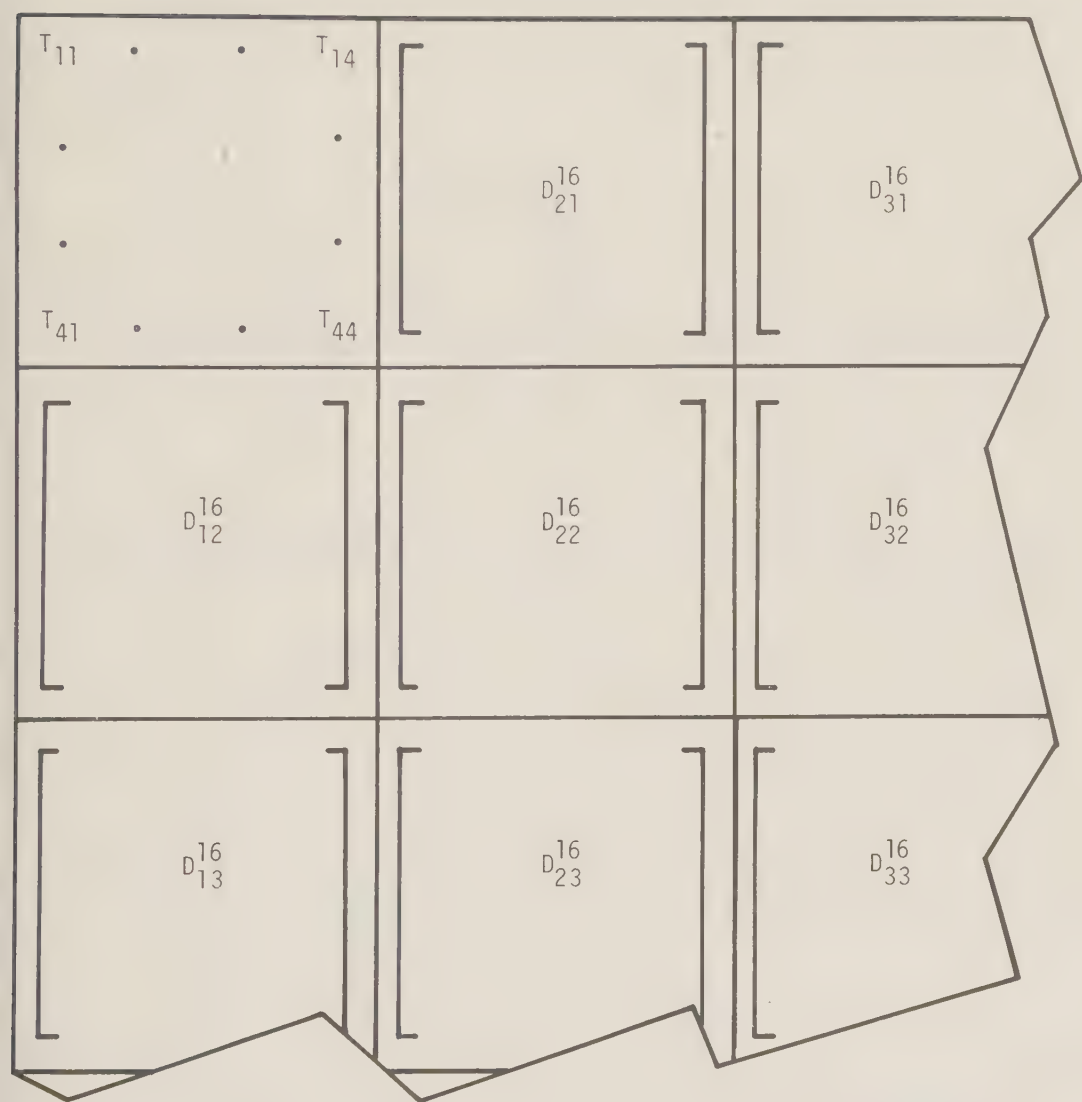


Figure 2.4. Scheme for threshold matrix assignment with a 4 x 4 matrix. The matrix is repeated both horizontally and vertically over the entire image.

successive thresholds should be as great as possible. This ensures a high spatial bandwidth in the resulting bilevel image.

To construct a matrix of thresholds with this property, one can start with a fundamental 2×2 matrix, Eq. (6)

$$d^4 = \begin{bmatrix} 3 & 1 \\ 0 & 2 \end{bmatrix} \quad (6)$$

where the numbers within the dither matrix indicate where numerically successive thresholds are placed. Note that the placement of 0 and 1 on a diagonal satisfies the condition that numerically successive thresholds should be spaced as far away from one another as possible. Thus, for a quantization range of 0 - 255 (8 bits and 255 corresponds to max intensity) a possible 2×2 dither matrix would be

$$d^4 = \begin{bmatrix} 192 & 64 \\ 0 & 128 \end{bmatrix} \quad (7)$$

This is the arrangements of dither thresholds subjectively derived by Limb (1969), except that the black and white levels are reversed to suit our definition.

In the derivation of larger sized matrices, one can use the simple recursion formula defined by Judice et al. (1974):

The generalized $n \times n$ dither matrix ($n = N$), where n has to be an integral power of 2, will be defined as follows:

$$d^N = \begin{bmatrix} \frac{N}{4d^4} + \frac{N}{3u^4} & \frac{N}{4d^4} + \frac{N}{u^4} \\ \frac{N}{4d^4} & \frac{N}{4d^4} + \frac{N}{2u^4} \end{bmatrix} \quad (8)$$

$$\text{where } u^N = \begin{bmatrix} 1 & 1 & \cdot & \cdot & 1 \\ 1 & 1 & \cdot & \cdot & 1 \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ 1 & 1 & & & 1 \end{bmatrix}$$

and thus

$$u^4 = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

A 16 threshold dither matrix derived from this definition is:

$$d^{16} = \begin{bmatrix} 15 & 7 & 13 & 5 \\ 3 & 11 & 1 & 9 \\ 12 & 4 & 14 & 6 \\ 0 & 8 & 2 & 10 \end{bmatrix} \quad (9)$$

and produces the following dither matrix for the quantization range 0-255:

$$D^{16} = \begin{bmatrix} 240 & 112 & 208 & 80 \\ 48 & 176 & 16 & 144 \\ 192 & 64 & 224 & 96 \\ 0 & 128 & 32 & 160 \end{bmatrix} \quad (10)$$

Figure 2.5 shows the seventeen possible display dot patterns which would be the result if a 4 x 4 dither matrix were applied on 4 x 4 uniform pixel intensity regions. In general, of course 2^{16} unique display dot patterns in each 4 x 4 region will appear depending on the actual pixel intensities.

Generalized, the thresholds within a particular quantization range can be written

$$T_{xy} = \frac{I_{\max} d^N}{N} = D_{ij}^N \quad (11)$$

where

- T_{xy} = threshold for the (x,y) pixel of the source image
- $I_{\max}$ = max intensity within the quantization range
- N = total number of thresholds within the dither matrix
- i = x modulo $N^{1/4}$
- j = y modulo $N^{1/4}$
- d^N = dither matrix with n thresholds as given in eq. (8).

We will later (Chapter 9) return to factors that must be considered when determining the size of the dither matrices used in our particular application.

2.2.5 Digital halftone thresholding

For comparison, we will also consider another threshold algorithm, namely the digital halftone algorithm. Here the thresholds are selected to imitate the halftone method used in conventional printing. This algo-

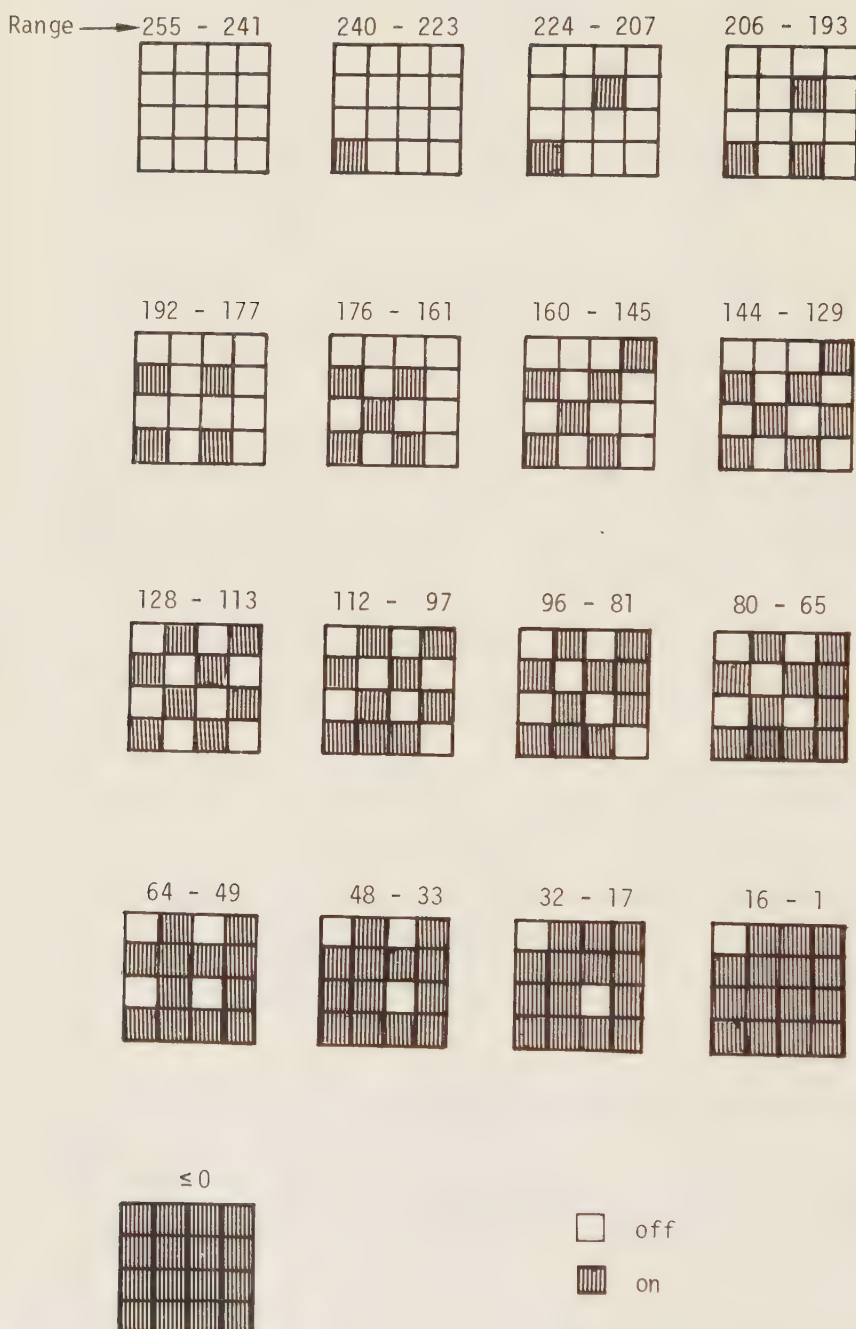


Figure 2.5. Uniform intensity ordered dither patterns using the 4 x 4 threshold matrix in eq. (10).

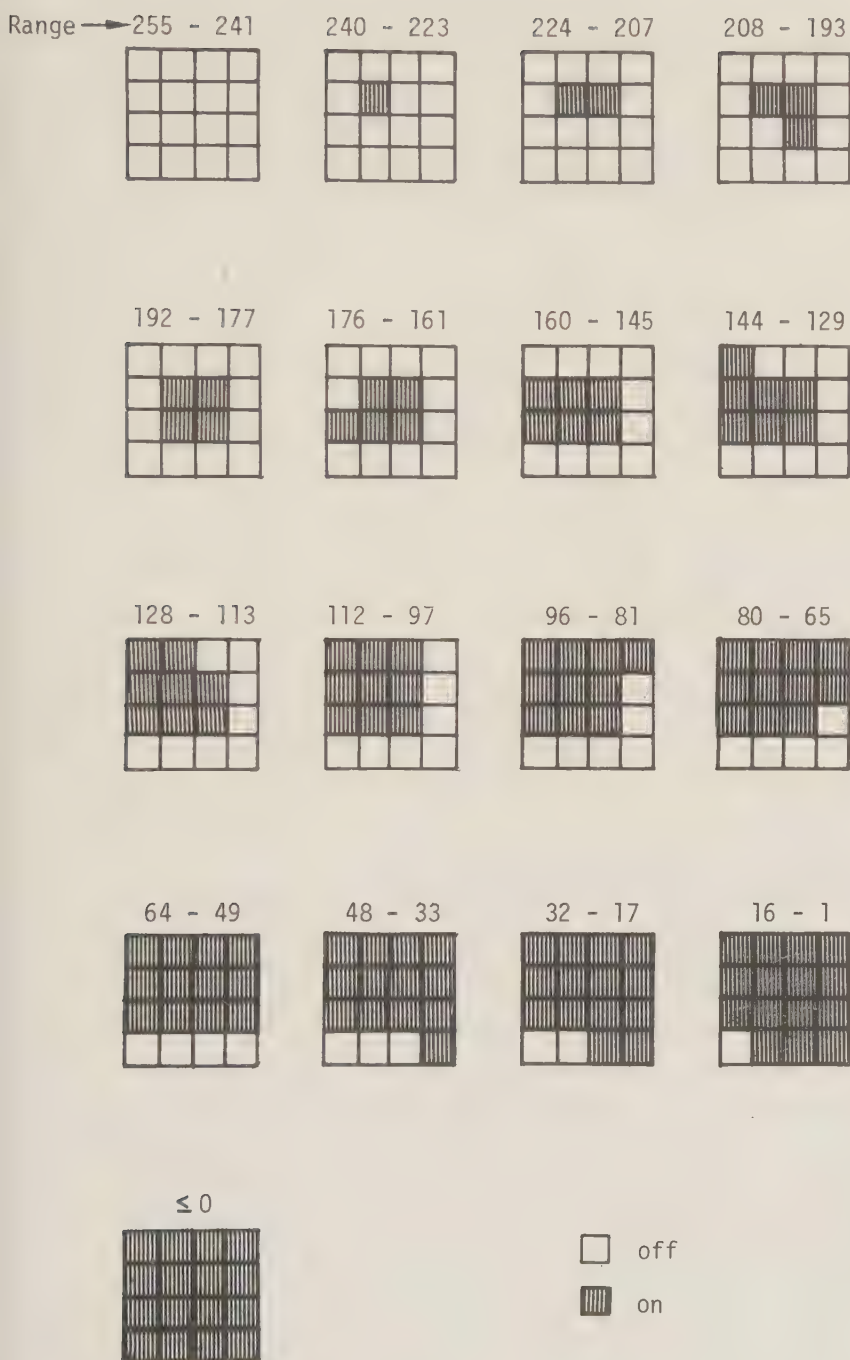


Figure 2.6. Uniform intensity digital halftone patterns using the 4 x 4 threshold matrix in eq. (13).

rithm is in a way the opposite of the ordered dither algorithm in as much as the thresholds are arranged in such a way that those which are numerically close are also spatially adjacent.

The matrix corresponding to the dither matrix in Eq. (9) will then be as follows:

$$h^{16} = \begin{bmatrix} 9 & 8 & 7 & 6 \\ 10 & 15 & 14 & 5 \\ 11 & 12 & 13 & 4 \\ 0 & 1 & 2 & 3 \end{bmatrix} \quad (12)$$

For the quantization range of 0-255, corresponding to Eq. (10), the matrix will be as follows:

$$H^{16} = \begin{bmatrix} 144 & 128 & 112 & 96 \\ 160 & 240 & 224 & 80 \\ 176 & 192 & 208 & 64 \\ 0 & 16 & 32 & 48 \end{bmatrix} \quad (13)$$

Figure 2.6 shows the seventeen possible display dot patterns which would be the result if a 4 x 4 digital halftone matrix were applied on 4 x 4 uniform pixel regions.

2.2.6 Adaptive versus non-adaptive algorithms

The principal advantage of non-adaptive thresholds is that the same thresholds are used for every image and that square matrix of thresholds is repeated in a checkerboard pattern across the entire source image. This minimizes the amount of hardware required for processing. Adaptive algorithms, on the other hand, require at least two or more line memories and additional electronic circuitry for the averaging process. A survey paper by Jarvis et al. (1976) addresses this fact. The paper contains a comparison and a discussion of adaptive pseudo-gray scale algorithms and one specific non-adaptive algorithm, the ordered dither. Even though the paper is concentrating on methods suitable for a bilevel ac plasma display, much of the information also applies to an ink jet plotter. It is shown in their application that the ordered dither technique provides an excellent rendition for a variety of images. When compared to adaptive algorithms, it appears that the additional storage

and processing associated with these algorithms is not warranted. That fact matches our desire for an easily implemented algorithm. The promising results shown in this paper and several other papers (Bayer 1973, Judice et al. 1974, and Judice 1976a) have led us to concentrate our efforts on the implementation of a non-adaptive threshold technique.

3 PRINCIPLE OF A CONTINUOUS-TONE TO BILEVEL IMAGE CONVERSION USING AN ORDERED DITHER THRESHOLD MATRIX

Figure 3.1 depicts the working principle of an ordered dither threshold matrix algorithm. In the figure the 4×4 ordered dither threshold matrix (eq. 10) is used. This 4×4 threshold algorithm corresponds to an $0.8 \times 0.8 \text{ mm}^2$ area (matrix area) in the bilevel ink jet plot.

As described earlier, the pixel intensities in the source image are quantized into an eight bit digital representation where a zero value corresponds to black and $2^8 - 1 = 255$ represents white. Thus, when the input signal is zero throughout a matrix area, a corresponding matrix in the plotter output should have all positions filled with ink dots. Vice versa, an input signal of 255 throughout a matrix area should cause all positions in a corresponding matrix in the plotter output to be free from ink dots. At intermediate input signal values the number of matrix positions not covered by ink should increase proportionally to the input signal values, following the dither patterns shown in Figure 2.5.

A small magnified area of a continuous-tone source image is shown in Figure 3.1. The figure also depicts how a 4×4 ordered dither threshold matrix is repeated throughout the area. Due to the construction of the drum scanner the source image pixels will be scanned consecutively in the vertical direction, beginning with the first scanning line at the left side of the image. Now, to obtain a pseudo-gray scale in the bilevel plot, each pixel is compared to its corresponding position in the dither threshold matrix. The decision to plot an ink dot is set by:

If $I \leq T$ then on (logical one) = plot
 else off (logical zero) = no plot

where I represents an 8 bit pixel intensity and T represents an 8 bit threshold in the matrix.

This comparison is made for each pixel throughout the source image thus yielding the result shown in Figure 3.1.

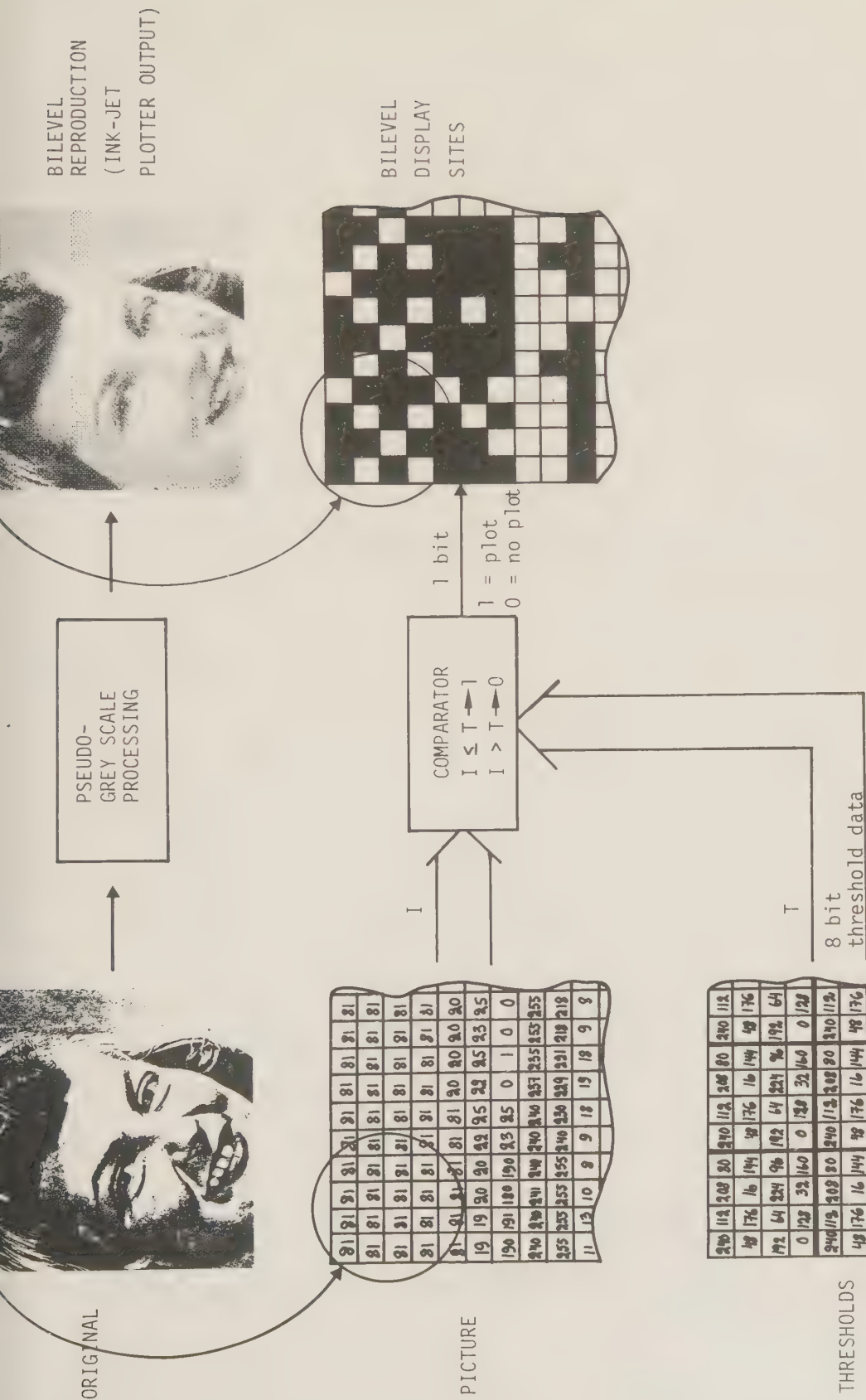


Figure 3.1. The principle of a continuous-tone to bilevel image conversion using an ordered dither threshold matrix.

4 CONTINUOUS-TONE TO BILEVEL IMAGE CONVERTER

4.1 Introduction

When designing a bilevel imaging system a decision must be made how to implement the processing of the image. The implementation can be carried out in three different ways:

1. a software solution
2. a hardware solution
3. a firmware solution which is a combination of software and hardware.

When selecting the solution described below, the following factors have to be considered:

- Realtime processing versus off-line processing
- Flexibility of system design
- Availability and capacity of computer systems
- Complete system cost.

4.1.1 Software implementation

Implementation of a software-based system is straightforward. All image-processing, except an analog to digital conversion, takes place in the computer system. This type of off-line processing allows great flexibility. At the same time the cost of special hardware within the system is kept at a minimum. The major drawbacks with a software-implementation are the large amount of data that must be stored and processed, as well as the time necessary for this procedure. For example, in our application an image $615 \times 665 \text{ mm}^2$ in 3 colors with a resolution of 5 lines/mm requires more than 30.6 million bytes of disc storage if, as normal, every pixel is represented by 1 byte/color. A software implementation is most advantageous if comparisons between different threshold algorithms, adaptive and non-adaptive, shall be made and processing time and cost are of little importance.

4.1.2 Hardware implementation

Implementation of a hardware-based system centers around the thresholding algorithms. Figure 4.1 depicts a functional block diagram of the

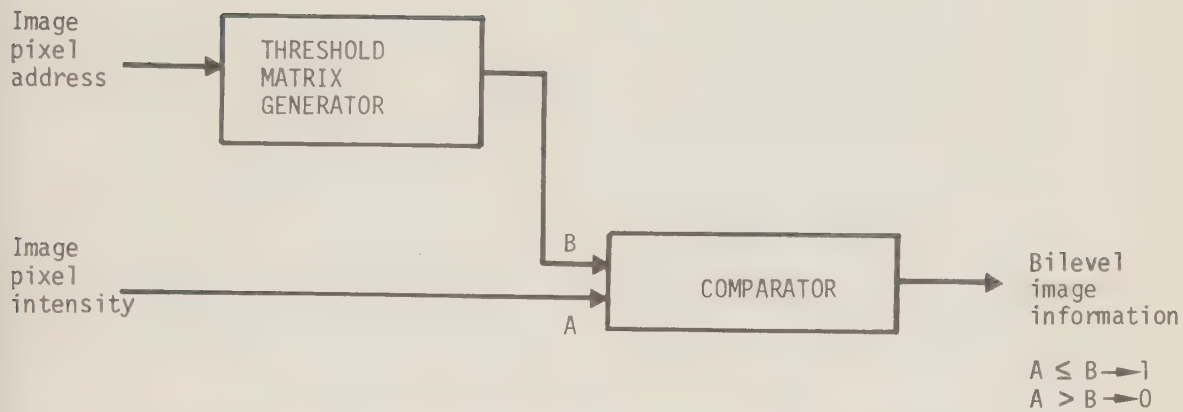


Figure 4.1. Functional block diagram of a hardware based bilevel converter. The pixel address generates a threshold in the threshold generator. This threshold is compared with the pixel's intensity in the comparator. Depending on the outcome of the comparison either a high or a low level appears at the output of the comparator. This hardware can be realized using clocked analog or digital circuits.

system. The input-signals to the system, i.e. image pixel intensity and image pixel address, generate a bilevel representation of the continuous-tone image through the threshold matrix generator and comparator as described in the previous chapter. Each image pixel address selects a threshold from the matrix and compares this threshold with the image pixel intensity. Depending on the result of this comparison, the circuit outputs a "high" or "low" level.

The hardware implementation can be based on clocked analog or digital circuitry. Clocked analog circuitry, where the threshold generator and comparator are analog devices, is advantageous if high speed processing (over 1 MHz) is desired. The disadvantages are the construction of a threshold generator using resistive voltage dividers to generate the thresholds, the hysteresis in analog comparators, and the DC-drift present in analog systems. The digital solution is easier to implement, the threshold generator can be constructed using ordinary ROMs and digital address counters, and the comparison is made in digital comparators without hysteresis. If high speed, over 1 MHz, is required, the digital solution will be costly due to the high price of fast A/D converters.

A hardware implementation requires very little computer processing and storage, as the hardware compresses the information, in realtime, 8 times before the information is stored. The major drawback is the poor flexibility of the system.

4.1.3 Firmware implementation

By combining software and hardware, the advantages of each of them can result in better solution without earlier mentioned drawbacks. Therefore we chose a firmware solution which is described in the following.

4.2 System design

We chose to base our bilevel scanner on a microprocessor system to give the system flexibility not only in the choice of threshold algorithms but also in scanning resolution and output media selection.

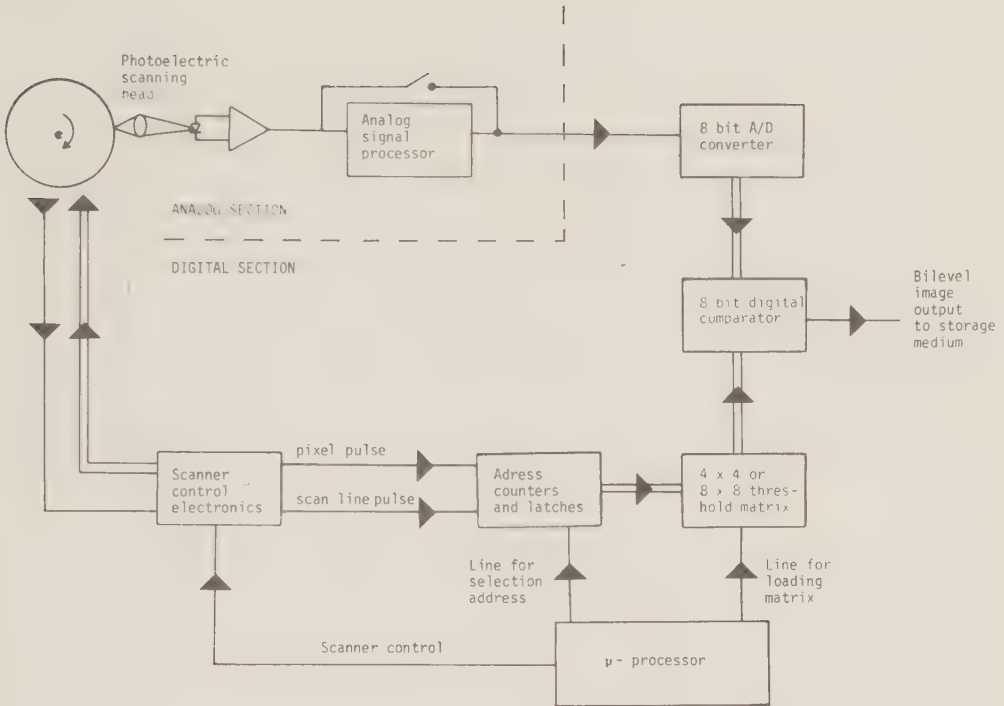


Figure 4.2. Functional block diagram of a bilevel scanner implemented in firmware. For clarity only one channel is shown. The analog section amplifies the input signal to suitable levels for the digital comparator section. It also allows some image processing such as grayscale expansion, compression and edge enhancement.

The digital section consists of comparator circuitry and a microprocessor system. The comparator circuitry compares the 8 bit intensity information from each continuous-tone image pixel with alternating thresholds from a threshold matrix generator.

The outcome of the comparison is only one bit for each color and pixel. Here an image compression by a factor 8:1 is achieved.

The microprocessor system also makes it easy for operators with only slight technical experience to use the scanner.

4.2.1 Hardware design

The hardware section consists of an analog and a digital section as shown in Figure 4.2 which depicts a simplified block diagram for one color only. Apart from amplifying the low level signals generated in the photodiodes the analog section can perform some image processing. Gray scale expansion and compression with or without gray scale offset can be achieved by changing the DC-level and amplification and edge enhancement can be carried out by using a differentiation circuit which emphasizes the edge information in the image.

The design of the analog section is described by Nilsson (1981). In this chapter only the design of the digital comparator section will be discussed.

4.2.2 Comparator circuitry

As the scanner was to be based on a microprocessor system it was natural to implement the threshold algorithm circuitry digitally.

Non-adaptive threshold algorithms are all based on some kind of matrix method as mentioned in the previous chapter. Figure 4.1 shows the principal solution of the comparator circuitry. In our digital firmware solution, the comparator is an 8-bit digital comparator, while the threshold matrix generator is realized using a random access memory with address counters.

A detailed block diagram showing the circuit for three colors is shown in Figure 4.3. The analog signal is A/D converted resulting in an 8 bit value of the reflected intensity. The conversion time, 4 μ s, is approximately 15 times faster than the highest frequency present in the video signals from the photodiodes in the scanner head. Therefore, no sample and hold circuits are used at the A/D converter inputs.

To allow for flexibility in the selection of threshold algorithms

the threshold generator matrices are stored in random access memories (RAM). During the normal scanning operation these RAMs are addressed by two binary counters, one row counter and one column counter. The row counter is clocked every 0.2 mm (i.e. every pixel) in the scan line direction, while the column counter is clocked once for every new scan line. This creates a repetitive matrix pattern which is compared with the intensity of each pixel in the continuous-tone image in the 8 bit digital comparator. The output from each comparator is the bilevel representation of the continuous-tone image in one color. As the scanner uses the three primary colors, cyan, magenta, and yellow, three identical channels are realized in the circuit.

Before starting the scanning operation, the RAMs containing threshold information for the three colors must be loaded. This loading is attained from the microprocessor which is connected through an I/O port to the RAMs. The RAMs allow matrix sizes up to 8 x 8 pixels to be used. As each color has its own matrix RAM, it is possible to use different thresholds for different colors.

4.2.3 Color offset adjustment

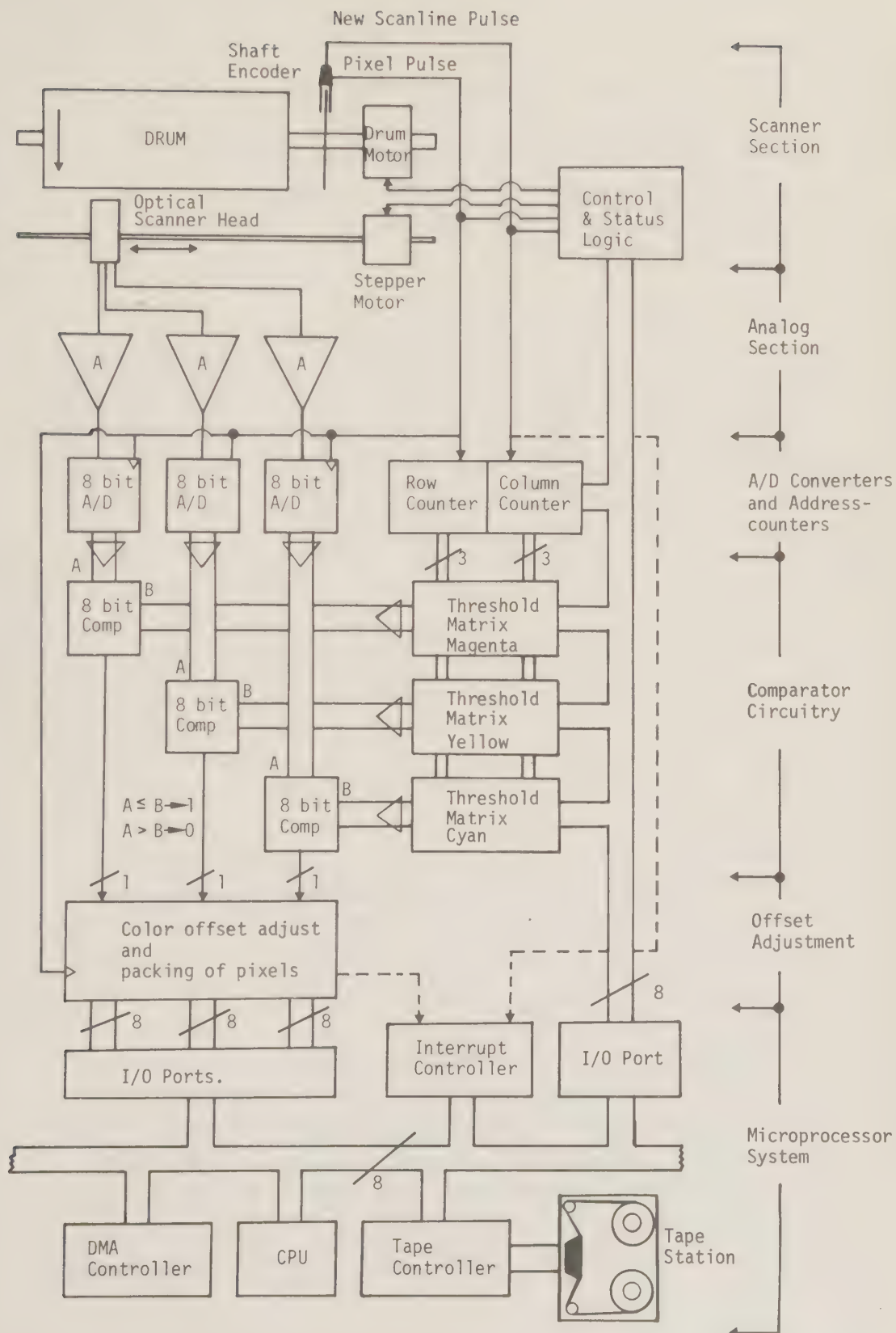
In an ideal optical scanner head the intensity information from one pixel can be processed simultaneously in all three colors. This requires that all three detectors, through their filters, can see the same pixel at the same time. To achieve this, color separation prisms or semi-reflective mirrors and filters can be used. Since these solutions are expensive, our scanner head uses a different approach (cf. Figure 4.4).

Three optical fibers carry the intensity information from the image to the three detectors. The inputs to the optical fibers are positioned close to each other along a line parallel to the drum rotation. This design introduces a position error of one pixel between adjacent colors in the scanning direction. This error is corrected in serial input, parallel output registers connected to the comparator outputs. This is achieved by selecting the outputs from the registers in such

Figure 4.3. The videosignal from each photodetector is amplified and A/D converted. This 8-bit digital signal is compared in the comparators with a digital threshold value stored in the threshold matrices. After correction for color offset, the result is packed together with 7 other pixel values to form a byte which is stored in the microprocessor memory. When a full scanline has been stored in the memory, the entire line is copied through DMA-transfers to a magnetic tape on a magnetic tape station. This is repeated until the entire image is stored on tape. Using this procedure the image information is compressed 8 times.

During the scanning the shaft encoder delivers information to the drum motor for constant speed, to the stepper motor for sideways movement of the optical scanner head, to the row and column counters for addressing the threshold matrices, to the A/D converter to start conversion of next pixel and to the color offset adjust and packing of pixel circuitry for reference when correcting color offset and packing the pixel information into bytes.

Prior to scanning the three threshold matrices are loaded from the microprocessor system using the row and column counters as address latches.



a way that the bilevel information in the three colors is synchronized.

The position error described here also causes a different start in each color matrix pattern as the matrices use the same row and column counters. This error is compensated for by suitable loading of the matrices.

4.2.4 The microprocessor system

The microprocessor system mainly transfers bilevel image information from the comparator circuitry to a magnetic tape station. This system will be described in detail by Nygren et al. 1982. It also performs other tasks such as

- scanning head position control
- magnetic tape station status control
- operator communication over a terminal, etc.

Due to the relatively high transfer rate the transfer of data is quite complex. The transfer from the comparator circuitry to the microprocessor memory is initiated by an interrupt every time 8 bits in each color have been generated. When a full scan line, consisting of up to 432 bytes in each color, is stored in the memory, another interrupt starts a direct memory access (DMA) transfer of this line from the memory to the magnetic tape station, where the bilevel information is stored on tape. The scanner could also be connected directly to a computer through a DMA-channel, but this requires special hardware and software for each new computer. Therefore, we favor the off-line version using a magnetic tape station. A magnetic tape is a medium most computers can handle.

The transfer between memory and magtape station must not slow down the normal program execution of the processor as this might result in a loss of data coming from the threshold hardware into memory. Therefore, a special DMA-controller was designed which, contrary to DMA-controllers commercially available, does not slow down the microprocessor's normal program execution (Nygren et al. 1980). This DMA-principle is called transparent DMA. It utilizes the address and da-

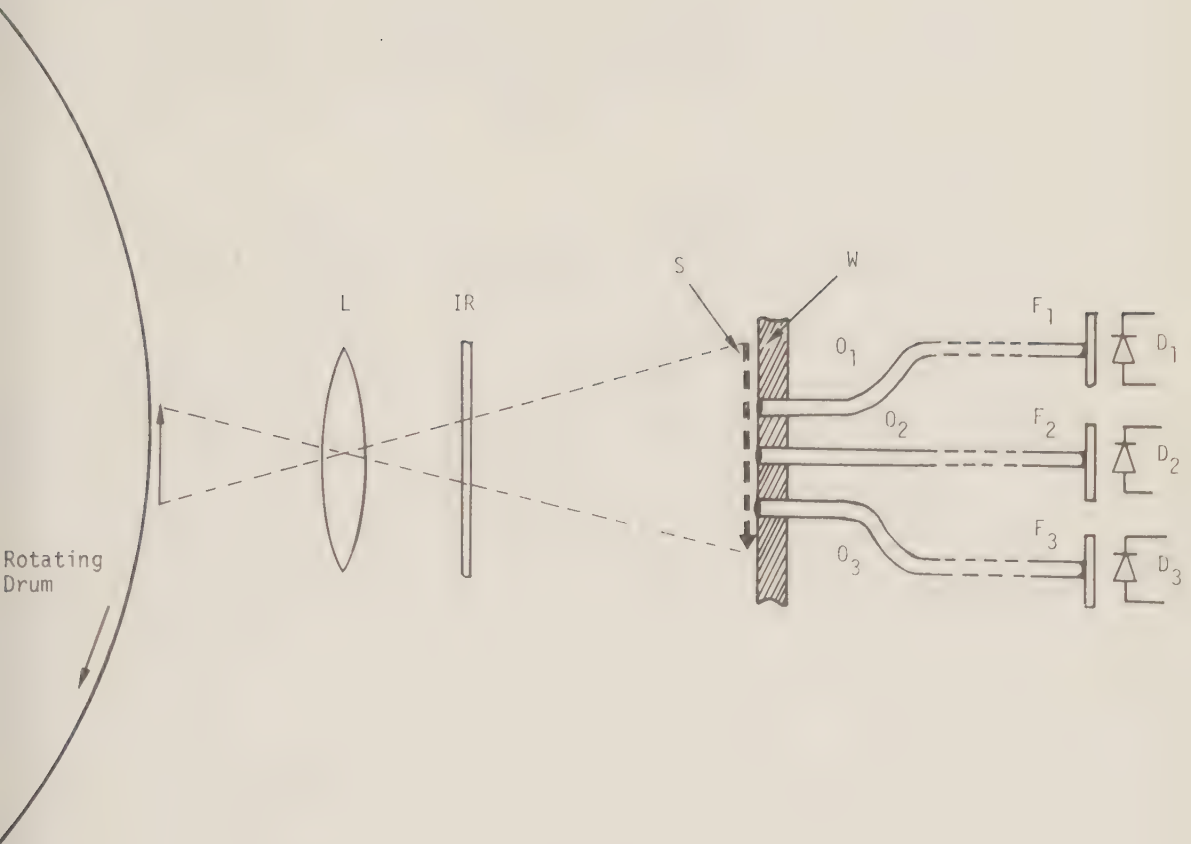


Figure 4.4. The lens L projects a small part of the image on the drum onto a surface S of wall W. In the wall three (or optional four) small holes are drilled close to each other along a line which is parallel to a scanning line (= parallel to the drum rotation). In each hole an optical fiber $O_1 - O_3$ is introduced which collects the light falling into its finely ground end and guides it through a color filter $F_1 - F_3$ onto the photodiodes $D_1 - D_3$. Color separation filters in front of the photodiodes $D_1 - D_3$ separate the pixel color into its tri-color contents.

ta busses in an instruction cycle when they are not required by the processor. This occurs at least once in every instruction, so the DMA-controller is working at speeds equal to or greater than the speed of commercially available controllers.

4.3 Details of circuitry

To fully understand the function of the converter circuitry some parts of the circuit will be discussed in more detail.

4.3.1 A/D converter circuitry

In the color scanner the same resolution as the one used in the Color Jet Plotter must be maintained. The plotting line density in the Color Jet Plotter is 5 lines per mm and to obtain this in the color scanner we must sample at least twice in each pixel to fulfill the sampling theorem. For this purpose the pixel pulse shown in the simplified block diagram 4.3 is used as input to the frequency doubling circuitry shown in Figure 4.5. The dual sampling and associated circuitry was deliberately excluded in Figure 4.3, as this had no importance for the understanding of the fundamental function of the scanner.

The pixel pulse, called BSYNK2, is a symmetrical squarewave signal, where the distance between two consecutive rising edges corresponds to an 0.2 movement on the drum surface. In the circuit shown every rising and falling edge of BSYNK2 is delayed in one of the two low-pass filters consisting of a capacitor and the resistance within the logic gate. BSYNK2 is also directly coupled to the exclusive -OR gate 8 at the output. The circuit generates a pulse for each transition in BSYNK2, where the width of the pulse is determined by the delay introduced by the LP-filters. This new signal is called BSYNK1, and as it generates two pulses in each pixel it is used to start the A/D conversions.

As the A/D converter (Figure 4.6a) uses the successive approximation method, it is important that the start pulse does not occur too close in time to the rising edge of the A/D converter clock, FITVA. Therefore, BSYNK1 is synchronized through a D-type flip-flop with the clock

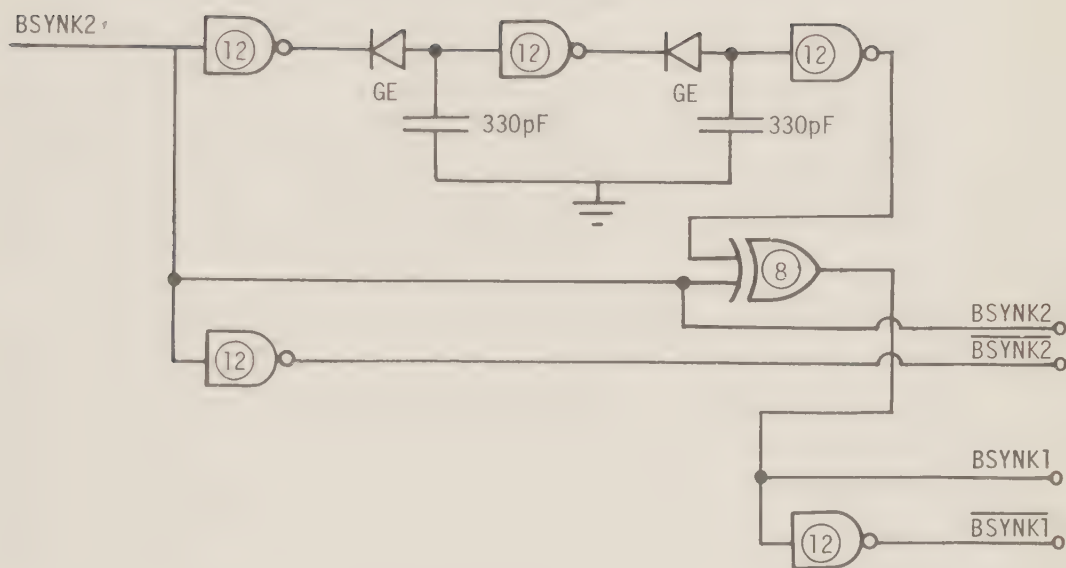


Figure 4.5. The output from the shaft encoder, BSYNK2, is a symmetrical squarewave, where the distance between two consecutive rising edges corresponds to an 0.2 mm movement on the drum surface. This signal is frequency doubled in the circuit shown above which outputs two pulses BSYNK1 for each 0.2 mm movement. The inverters (12) all have Schmitt-trigger inputs.

FITVA before it starts the A/D conversion (Figure 4.6a).

A timing diagram over an A/D conversion is shown in Figure 4.6b. A conversion of 1 pixel, corresponding to two conversions into 8 bits takes approximately $4\ \mu\text{s}$ each, and this time is much shorter than the time it takes to move the drum 0.2 mm at maximum speed. Because of this we do not use sample and hold amplifiers at the A/D converter inputs.

The parallel outputs of the A/D converters are connected to the 8-bit digital comparators. The other inputs of the comparator are connected to the RAMs containing threshold information.

4.3.2 Comparator circuitry

The threshold matrices not shown in Figure 4.6a are clocked by BSYNK2 once in every pixel. As two A/D conversions occur during one pixel the results from both conversions are compared with the same threshold value. The two samples in each pixel create two bits per pixel information and this is reduced through a majority rule logic and associated clocked circuitry to one bit pixel before entering the microprocessor system. The reduction of information is made in the two serial input parallel output registers (SIPO 11 and 8) and the logic gates 3 and 4 located between them (cf. Figure 4.6a). The majority rule logic asynchronously compares three logic inputs - in our application three consecutive comparator results - and outputs the logic level which is in majority. This increases spatial resolution in the scanning direction.

The SIPO registers have 8 parallel outputs each. In SIPO 11 only 3 of the outputs are used. The selection of the 3 outputs depends on the color offset error introduced in the scanner head. This has been discussed in section 4.2.3. The SIPO 8 uses all 8 outputs, and is used to convert the single bit stream into an 8 bit (byte) stream to the microprocessor system.

The reduction of pixel information is achieved by using different

clocks to the two SIPOs and the majority rule logic inbetween.

SIPO 8 is clocked at half the frequency of SIPO 11, thus every other result from the majority rule logic is lost. This means that every pixel value passed on to the microprocessor system depends on the two samples within the pixel and the second sample of the previous pixel.

The dual sampling of each pixel and the weighing of samples gives a better spatial resolution in the scanning direction than in the horizontal direction. This can be compensated for by moving the scanner head only 0.1 mm for each new scanline and applying the majority rule in software for the horizontal direction after the digitized image has been introduced into a host-computer system.

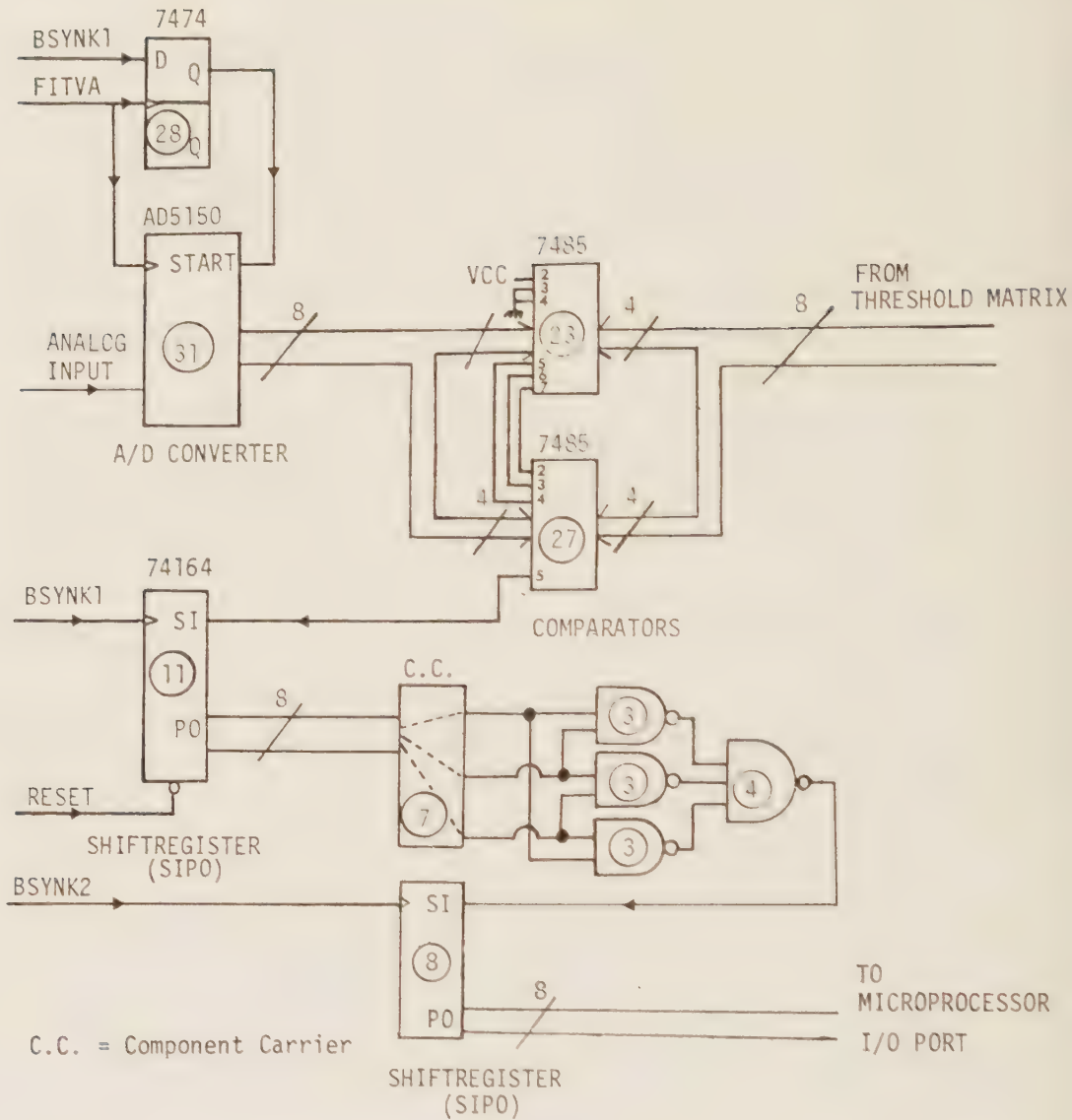


Figure 4.6a. The signal BSYNK1 is synchronized to the A/D converter clock FITVA before it starts the conversion to avoid error in the A/D conversion. The result of the A/D conversion is compared to a threshold value generated by the threshold matrices. The result of the comparison is shifted into a serial input/parallel output register (SIPO (11)). This register, the following logic gates and SIPO (8) register reduce the 2 bits per pixel information acquired through two A/D conversions in each pixel to 1 bit per pixel.

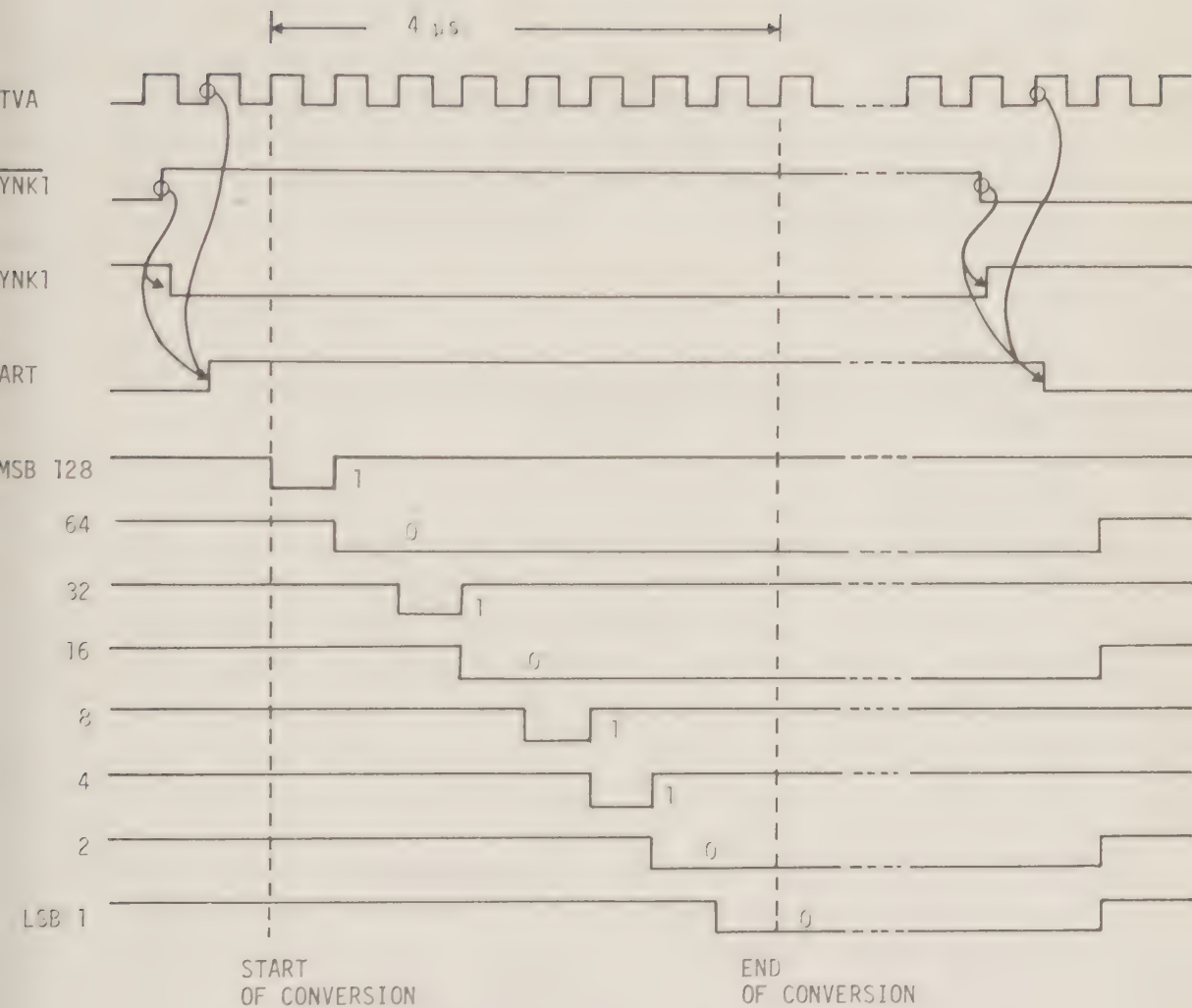


Figure 4.6b. A/D conversion on a successive approximation converter. To meet the setup requirements for the start pulse of the converter, the start signal (BSYNK1) is synchronized to the clock FITVA. The diagram shows the conversion of +1.75V into 1010 1100 using an analog input range of $\pm 5V$.

5 THE INK JET PLOTTER CHARACTERISTICS

5.1 Introduction

All images that are scanned will eventually be reproduced by the Ink Jet Plotter. Hence, any nonlinearities in the ink jet printing process could cause an unsatisfactory reproduction, even if the scanning of the original is faultless. Therefore, in the following these nonlinearities are studied in some detail.

In this chapter the nonlinearities in the plotting of one color only are treated. In the actual experiments magenta ink was used. The full color printing process using a mixture of the three colors magenta, cyan, and yellow, will be considered in chapter 10.

5.2 Basics

If one thinks of white paper as a reflector of light, the function of ink is to attenuate the light that is reflected from the paper. If light of the intensity of I_0 is directed towards the surface and the reflected light is I_1 , then the definition of reflectance R of the object is (Tupper, 1966):

$$R = \frac{I_1}{I_0} \quad (14)$$

As already noted in the introduction a continuous-tone original could be reproduced using a combination of the patterns within given small areas. However, these areas must be small enough so that the eye does not resolve the individual dot, but integrates over the area. The size of the area, in our application, is directly related to the size of the threshold matrix and the size of the plotted dots. The Ink Jet Plotter uses a dot size of $0.2 \times 0.2 \text{ mm}^2$, thus a 4×4 matrix will cover an area of $0.8 \times 0.8 \text{ mm}^2$.

By covering one element in such a 4×4 matrix with ink one sixteenth of the light normally reflected from the white paper is absorbed. Thus, a light gray is produced by a larger number of such matrices. Generally, the higher percentage of the matrix area that is covered by the

dots (dot area), the darker the gray. So, by varying the number of dots in the matrix and thus the percentage of matrix area covered by ink, a full range of gray tones (lightness) within a given color can be obtained.

Using our 4 x 4 matrix a possible range of $4 \times 4 + 1 = 17$ levels of gray (white included) can be generated (cf. Figure 5.1). Theoretically the reflectance from such a matrix is given by the equation

$$R = \frac{I_1}{I_0} = \frac{N-n}{N} \quad (15)$$

where N is the number of matrix elements and n the number of matrix positions covered by ink (dot area). If the reflectance actually generated by the ink jet printing process does not follow this relation, nonlinearities in the reproduction of the original must be expected. Therefore, it is of importance to check if the reflectance of matrices generated by the ink jet agrees with the theoretical formula given above.

5.3 Measurements and results

Computer generated gray scale patterns consisting of matrices with increasing number of dots were used to simulate an ideal grayscale having 17 steps. The dots were arranged within a repeated 4 x 4 matrix, using the order indicated by the dither matrices shown in Figure 2.5. The patterns were plotted at a normal speed, corresponding to a drum surface speed of 4 m/s.

A reflection densitometer of type McBeth Quanta Log RD-107P was used to measure the densities of the patterns. The instrument measures the diffuse reflection density (S) by collecting the portion of perpendicularly incident light reflected from a spot of the sample with a diameter of 3.2 mm (averaging over approx. 12 matrix areas) in an elevation direction of $45^\circ \pm 5^\circ$. This light falls on the cathode of a photomultiplier operated in a special circuit producing a linear density scale. Since the patterns were plotted with magenta ink, the green filter of the densitometer (Kodak Wratten Filter K58) was used. The reflectance R was calculated from the density values S using the relation (Tupper, 1966):

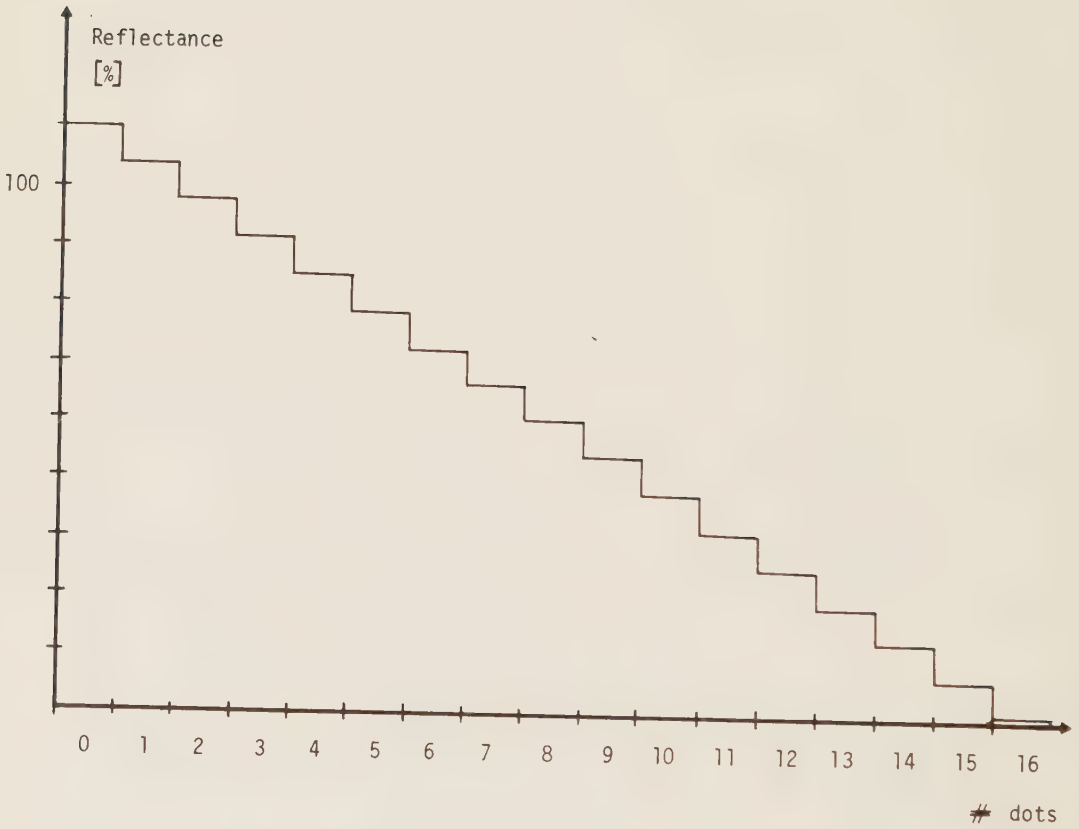


Figure 5.1. Reflectance, in percent, from an ideal white paper as a function of the number of ink dots in a 4 x 4 matrix (from eq. (15)). The diagram depicts the 17 levels of gray (white included) that can be generated.

$$S = {}^{10}\log \frac{1}{R} \quad (16)$$

thus $R = 10^{-S}$.

The results of the measurements on the dither patterns are shown in Figure 5.2. This shows that the number of dots plotted by the Ink Jet Plotter is a nonlinear function of reflection. Instead (cf. Figure 5.3) the number of dots shows an almost linear relation to the reflection density.

A curve fitting program, based on least square methods (Hp 9835 System 35 Software Manual, 1979) was used to evaluate the measured reflectance curve. It was fitted to a linear and exponential function. A coefficient of determination, r^2 , was calculated from

$$r^2 = \frac{\text{explained variation of } Y}{\text{total variation of } Y} = \frac{\sum(\hat{Y}_i - \bar{Y})^2}{\sum(Y_i - \bar{Y})^2} \quad (17)$$

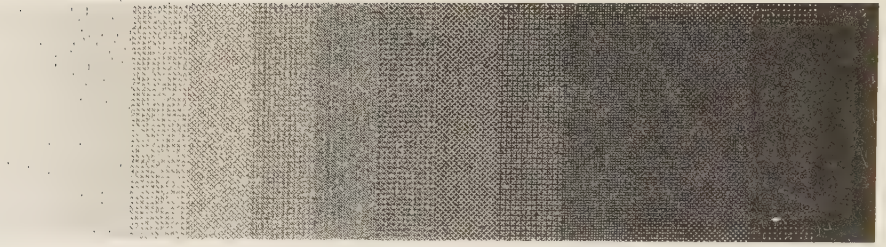
where Y_i represents the actual data being tested

$\hat{Y}_i$ represents the estimated value from the linear
or exponential function

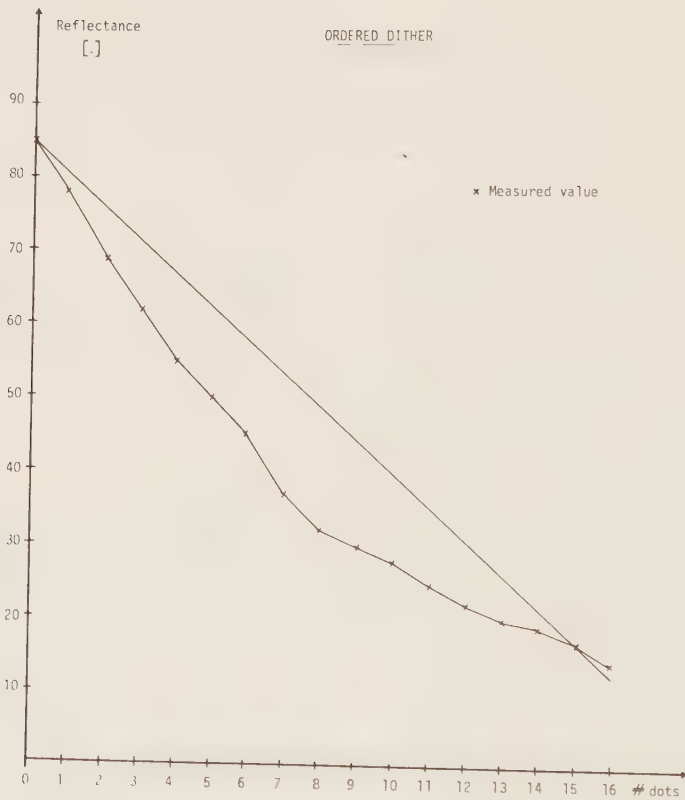
$\bar{Y}$ represents the mean of the data being tested.

Thus r^2 indicates the quality of the fitting achieved by regression as the proportion of total variation of the data that are explained by fitting the regression. Values of r^2 close to 1.00 indicate a better fit than values close to zero.

The measured reflectance curve in Figure 5.2 gave $r^2 = 0.935$ when tested for linearity, and $r^2 = 0.996$ when tested for exponential shape. Similar measurements were made using a gray scale generated by matrices using the digital halftone dot pattern shown in Figure 2.6. Here the reflectance curve (cf. Figure 5.4) seems to be more linear compared with the reflectance curve from the dither pattern in Figure 5.2. This is also confirmed by the curve fitting test which gave an $r^2 = 0.977$ in the linear fit. However, the regression test still shows that an exponential curve has a closer fit, with $r^2 = 0.991$.



a



b

Figure 5.2. (a) A computer generated ordered dither pattern with a linearly increasing number of ink dots, plotted using the ink jet plotter (magenta ink). (b) The measured reflectance from the patterns in (a).

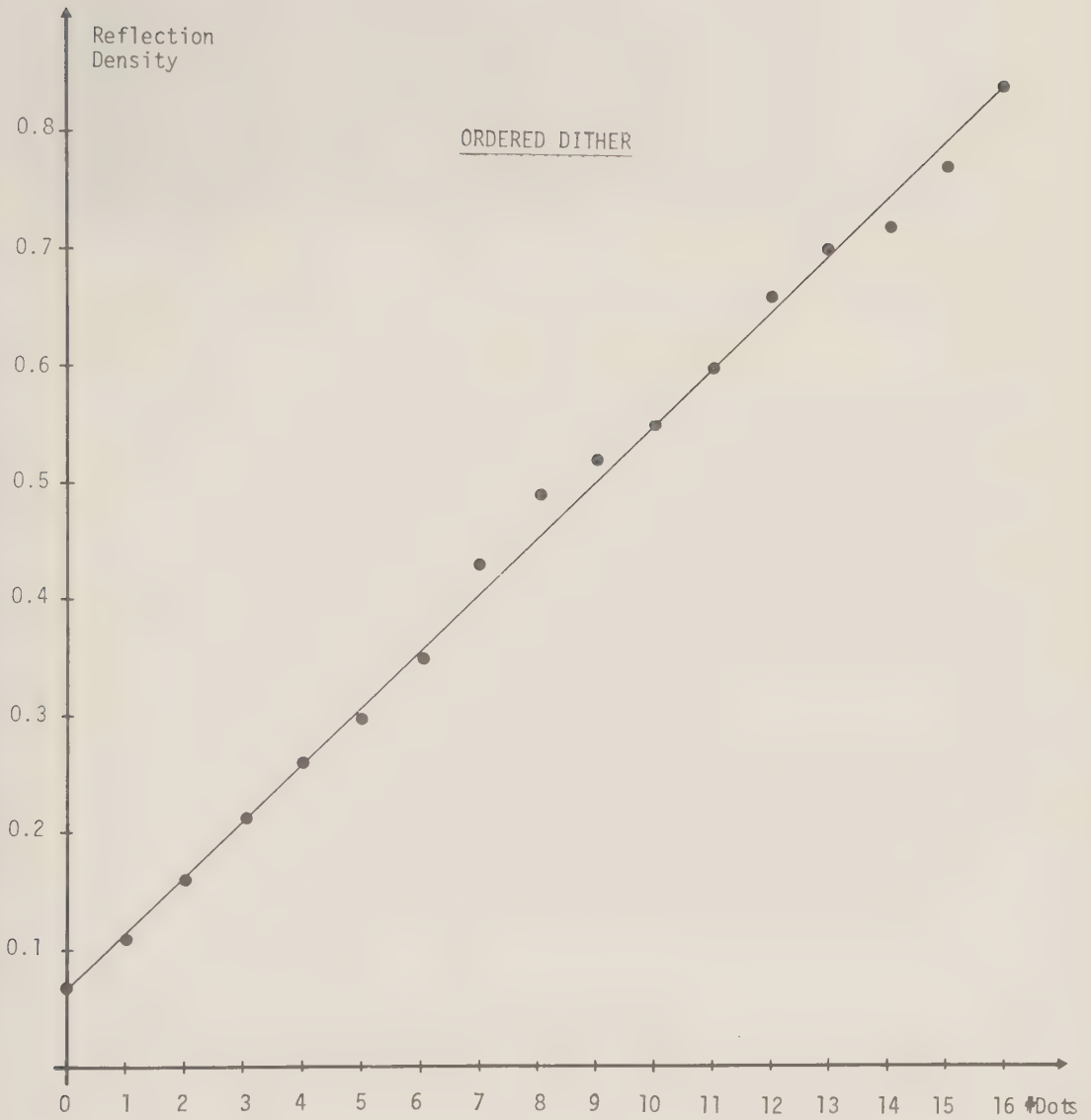


Figure 5.3. The measured reflection density of the ordered dither patterns in Figure 5.2a.

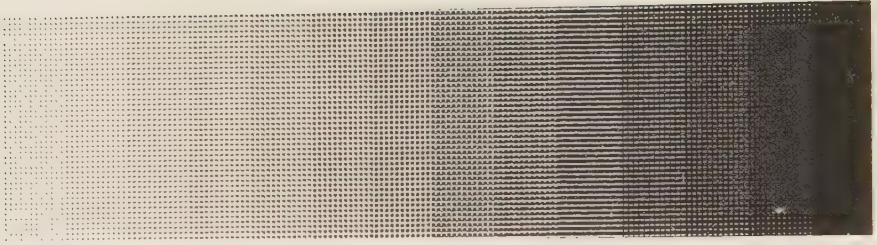
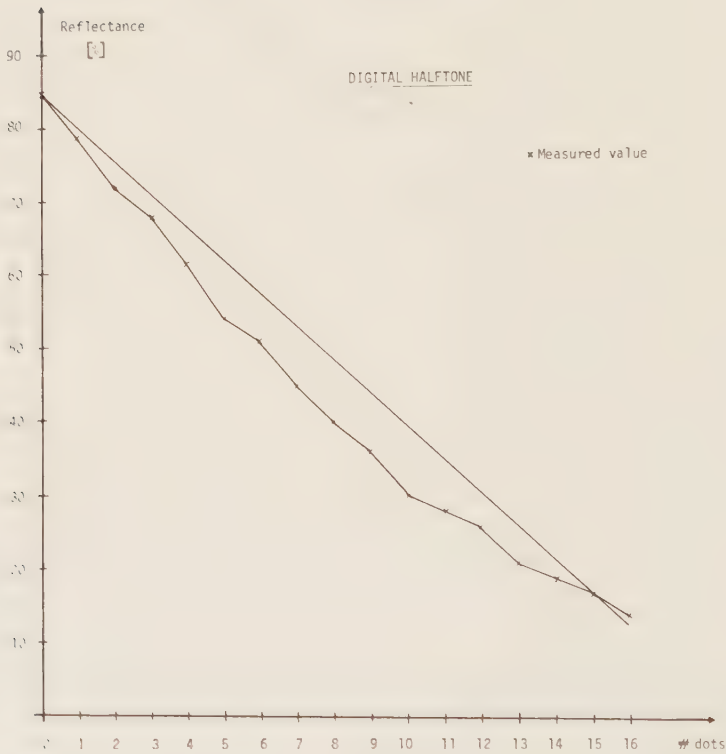
**a****b**

Figure 5.4. (a) A computer generated digital half-tone pattern with a linearly increasing number of ink dots, plotted using the ink jet plotter (magenta ink). (b) The measured reflectance from the patterns in (a).

Thus the measured reflectance seems to be pattern dependent, and not only a function of the number of plotted ink dots. This is a somewhat surprising result which, however, can be explained after a closer inspection of the plotting process.

5.4 Discussion of the results

Densitometer measurements of the white paper used in the experiments (Baryte paper) show a maximum reflectance of 85%. Measuring an area fully covered by magenta ink, the reading is 12.6%. This means that ideally one dot would absorb $(85 - 12.6)/16 = 4.5\%$.

A magnified view of some ink dots from a dither pattern plotted at a normal speed of 4 m/s (cf. Figure 5.5) shows, however, that

1. Even if the number of dots within one 4×4 matrix is a maximum of 16, there is still some area left of the white paper. Thus the ink does not fill out the entire $0.2 \times 0.2 \text{ mm}^2$ dot area as required. This means that the minimum reflectance achieved is measured to $\approx 14\%$, instead of the ideal 12.6%.
2. When one single dot is printed there is always some additional splatter of ink around the dot, most of it in the rotation direction (cf. Figure 5.6a). Therefore the plotting of two consecutive dots will not double the amount of splatter that one single dot creates (cf. Figure 5.6b).

In the model that predicts the results with these artifacts in the plotting process, the contribution from each dot to the total absorption has to be position-dependent. A look at the patterns in Figure 2.5 shows that, starting from the white paper, only single isolated dots are plotted in the first 9 patterns. Thereafter, in patterns 10 to 17 an additional dot is always filling the space between two "already existing" dots. This leads us to the following explanation:

To begin with, let us calculate the contribution of splatter. To this end, set the contribution to absorption from one single dot to 6.6%. This number is derived from measurements of single dots only, and thus

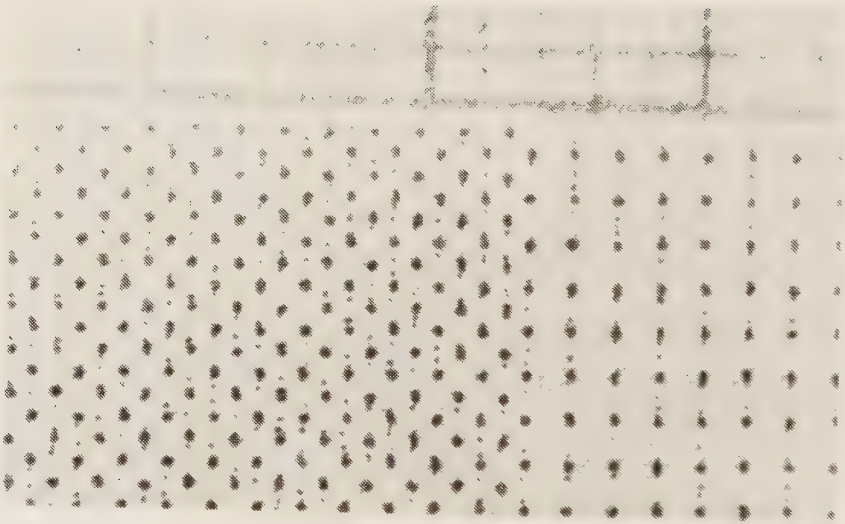


Figure 5.5. A magnified photograph of a large number of single ink dots. The large percentage of splatter is clearly visible. (A millimeter scale on a drawing paper depicts the magnification).



Figure 5.6. Contributions to absorption of light from ink dots, used to explain the non-linearities in the ink jet plots of ordered dither and digital halftone patterns.

(a) A single ink dot. Contribution to the absorption of light is measured to an average of 6.6%.

(b) Two consecutive ink dots. Contribution to the absorption of light from the state in (a) to this state is $6.6\% - 2.2\%$ (splatter) = 4.4%.

(c) One additional ink dot, between two "already existing" in dots. Contribution to absorption of light when going from state 1 to state 2 is $6.6\% - 2.2\%$ (own splatter) - 2.2% (splatter "already existing") = 2.2%.

included the splatter around the dot. Further, since the difference between the minimum reflectance achieved and the minimum reflectance possible $14\% - 12.6\% = 1.4\%$, the loss in absorption per dot is $1.4\%/16 = 0.1\%$. The contribution of absorption from the splatter is thus $6.6\% - (4.5\% - 0.1\%) = 2.2\%$.

Hence, when the difference between two dot patterns is a dot filling up the space between two "already existing" dots in the plotting direction, the contribution to absorption is found to be 2.2% as calculated in Figure 5.6c.

A graph calculated for the dither patterns shown in Figure 2.5 using this explanation is shown in Figure 5.7. For comparison the densitometer results from Figure 5.2 are included. As can be seen the predictions from the model correspond fairly well with the measured values.

The same model can be applied to predict the results from the digital halftone patterns. The only difference is that now we also have to consider the contribution to absorption from a dot added adjacent, before or after an "already existing" dot (cf. Figure 5.6b). Its absorption is found to be 4.4%. Also in this case calculations using the explanation above are in good agreement with the densitometer measurements (cf. Figure 5.8), even though all variations are not fully explained.

5.5 Conclusions

The ordered dither dot patterns have the highest possible frequency of on and off dots. However, it seems that the Ink Jet Plotter does not permit such high bandwidth switching without introducing artifacts in the printed dots. The dots tend to have a wider spread on the paper dependent on the local dot density. The result will be an overall darkening of the dithered rendition of an image. This could, however, be corrected by an appropriate modification of the dither thresholds, as will be discussed in chapter 7. This essentially corresponds to a gamma correction of the original video signal.

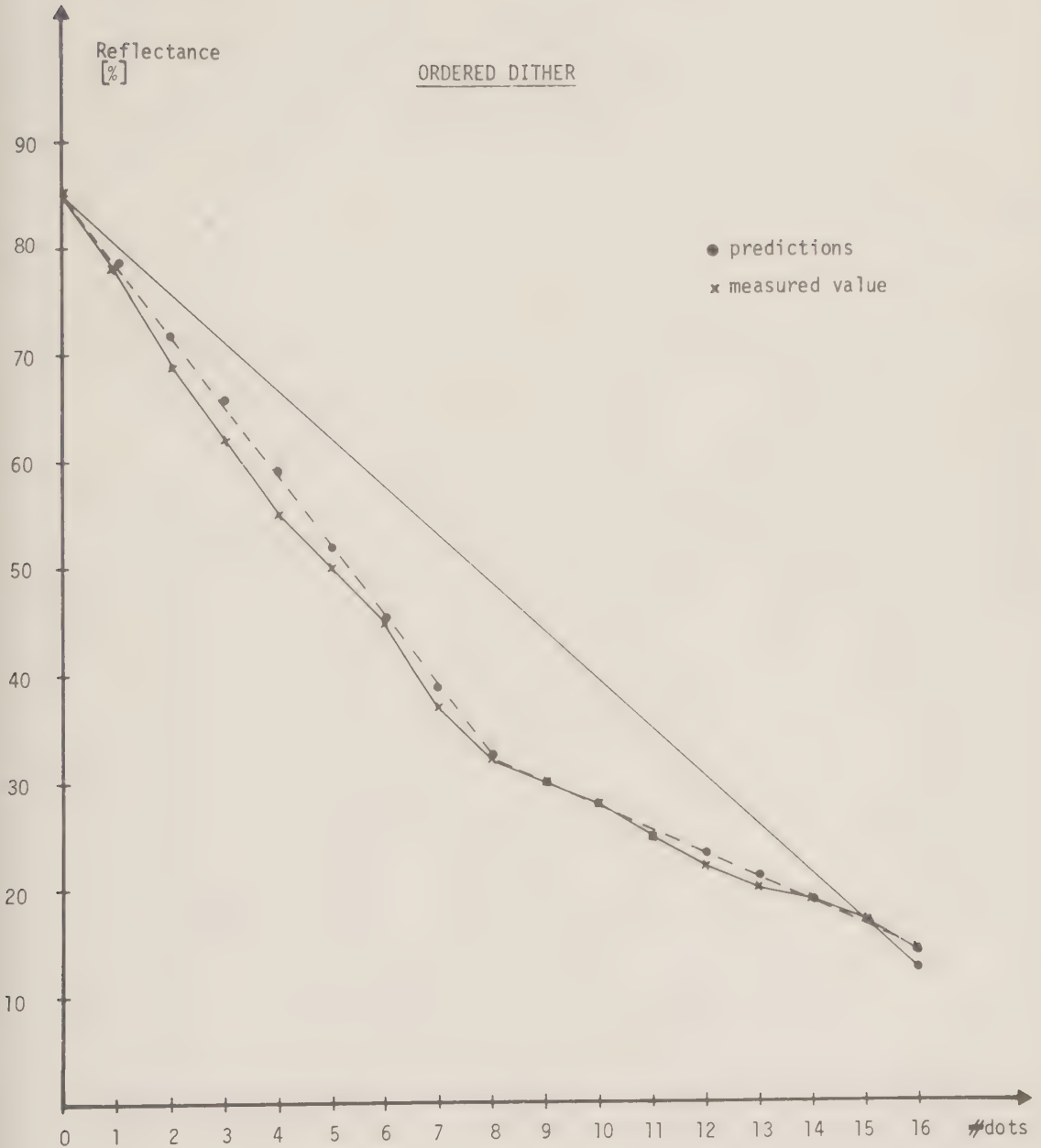


Figure 5.7. Predicted reflectance (---) and measured reflectance (—) from the ordered dither patterns. The predictions are based on the absorption percentages given in Figure 5.6.

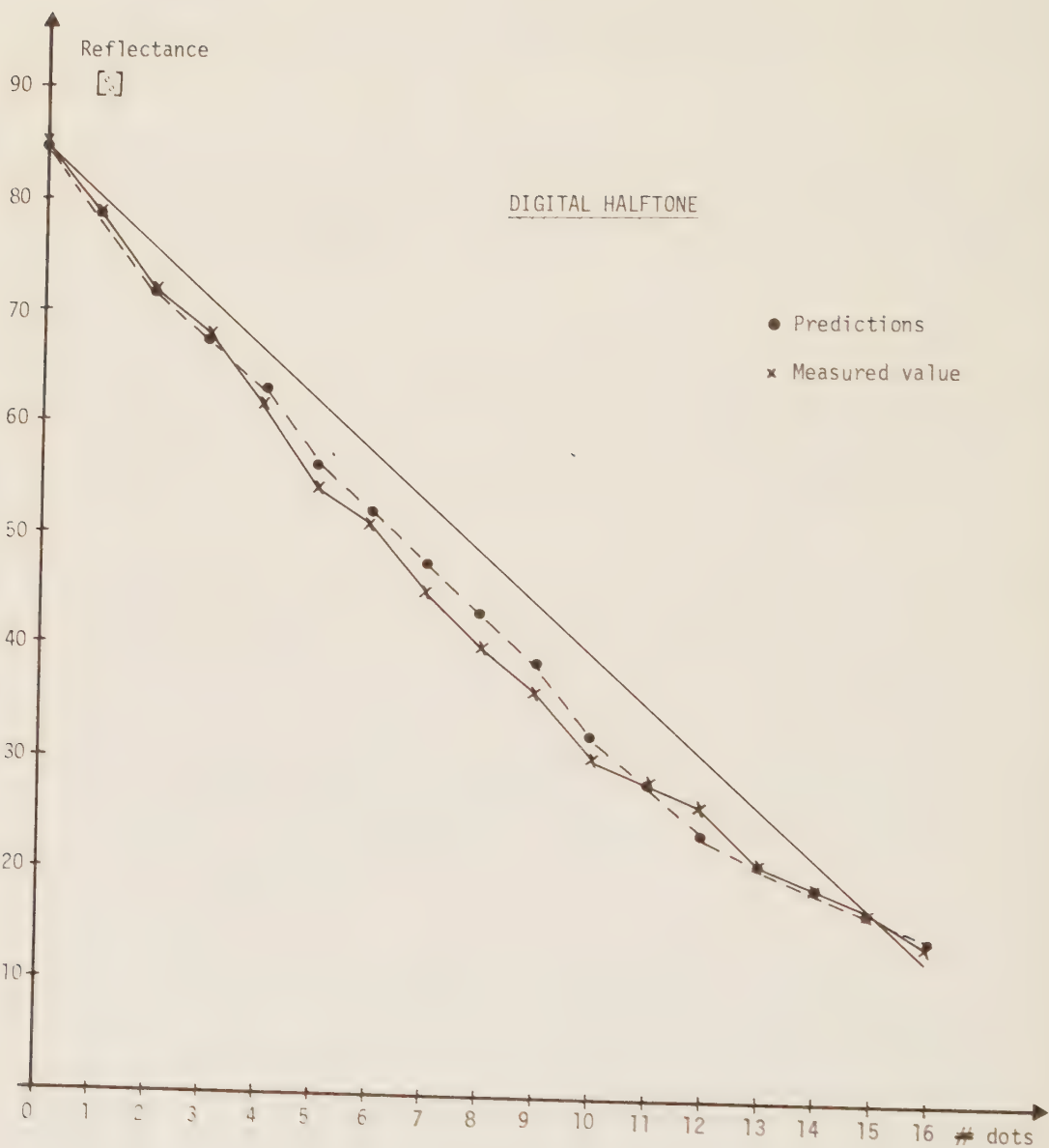


Figure 5.8. Predicted reflectance (---) and measured reflectance (—) from the digital halftone patterns. The predictions are based on the absorption percentages given in Figure 5.6.

On the other hand, the dots in the digital halftone patterns are arranged so that the growing number of dots are always spatially adjacent. In this case the dot splatter on the paper is more likely to fall into another dot than into a region which is white. This explains the difference in the density measurements found between the two patterns.

6 SCANNER CHARACTERISTICS

6.1 Introduction

It has been pointed out elsewhere (Nilsson et al. 1981) that the scanner uses essentially the same mechanical construction as the ink jet plotter described by Bladh et al. (1979), but with the recording head replaced by a specially developed scanning head. A detailed description of the mechanical and optical assembly of this scanning head as well as the photodiode detectors and their amplifiers can be found in the report "A color separating optical scanner head" (Nilsson 1981). This report also describes the characteristics of the photodiode detectors and the signal generated by the amplifiers.

In this chapter only those characteristics will be discussed that could possibly influence the distribution of threshold values used in the ordered dither and digital halftone matrices. Their influence on the threshold matrix will be discussed in chapter 7.

6.2 A description of the principle of the scanner head

Figure 4.4 shows the principle of the scanner head. Light from a halogen lamp not shown in the figure is slightly focused on the original to be scanned which is fastened to the rotating drum. Part of this incident light is reflected and the rest is absorbed. The reflected part passes through a lens system and an IR filter. The lens system magnifies a pixel on the drum 4 times before it is focused on the ends of three optic fibers. The optic fibers act as apertures that will determine the size of the pixel scanned.

A photodiode detector with a color filter is placed at the other end of each optical fiber. Different colored filters are used in front of the detectors, thereby achieving a color separation of the original (see also chapter 10). Normally, the Kodak Wratten filters K25(red), K58(green), and K47(blue) are used for the separation of cyan, magenta, and yellow, respectively. The electronic circuitry in the scanner head provides the option of edge enhancement along the scan line during a scanning. This option has been used in all experiments and measurements in the com-

ing chapters.

6.3 Detector response

Nilsson (1981) shows that the photodiode detectors respond linearly to the intensity of the light being reflected, i.e. reflectance. It is also shown that the only difference between the color channels is the amplification used to achieve the full output amplitude required for the A/D-converters. This is due to the spectral content of the light from the halogen lamp, the variations in absorption of the optical filters, and the spectral sensitivity of the detector. The amplification will affect the signal to noise ratio in the channels as shown in Table 6.1.

The dynamic voltage range of the input signal to the A/D-converter is $\pm 5V$, thus the noise levels correspond to between 4 and 6 quantization levels depending on the color channel.

Detected color	Noise V_{p-p} (mV)	S/N ratio (dB)
Magenta	180	35
Cyan	200	34
Yellow	250	32

Table 6.1. Noise levels in the three color channels.

7 THRESHOLD MODIFICATIONS DUE TO THE CHARACTERISTICS OF THE INPUT AND OUTPUT DEVICES

7.1 Introduction

Most applications of non-adaptive threshold techniques found in the literature use threshold matrices with uniform spacing between the thresholds throughout the quantization range (Bayer 1978, Jarvis et al. 1976, Judice et al. 1974, and Lippe1 et al. 1971). Two such examples of matrices are the ordered dither threshold matrix shown in Figure 7.2a and the digital threshold halftone matrix in Figure 7.2b.

The uniform spacing of the thresholds across the quantization range provides a relatively accurate linear mapping between input and output. However, this implies that the input and output devices are linearly related in order to achieve a good reproduction. In most systems this is achieved by electronic circuitry that compensates for any non-linearities within the system (gamma correction). One example of this is the TV-camera and the TV-receiver system: The TV-camera tube does not register intensities in a linear manner, but this artifact is corrected in the electronic circuitry of the camera.

In the present apparatus the nonlinearity problem is taken care of without gamma correction in the analog electronic circuitry. Instead we make all the corrections by adjusting the steps between consecutive thresholds in the matrices. In this way we achieve a cheaper and more flexible solution than to use an electronic compensation.

7.2 Determination of input/output relation

The properties of both the Ink Jet Plotter and the scanner head detectors have been described in earlier chapters. In chapter 5 it was shown that the number of ink dots printed within a given small matrix area (4 x 4 dots) was an almost linear function of the measured reflection density from that area. This was especially true when the ink dots were plotted following the dither pattern in Figure 2.5.

From chapter 6 we find that the detectors in the scanner head respond

linearly to the reflectance from each pixel of the source image. Thus we have an approximate input/output relation

$$R_{in} = 10^{-S_{out}} \quad (18)$$

where S_{out} = reflection density of the reproduction
 R_{in} = detected reflectance.

Thus, in order to achieve a good reproduction of the original color shades the input reflectances must be converted to their corresponding density value.

7.3 Determination of thresholds in a conversion matrix

A conventional solution for conversion of input reflectance to density would be to use an exponential amplifier in each of the three color channels in the scanner head. Then each pixel reflectance value would be converted to a density value before it was compared to a threshold from the threshold matrix. Using this hardware conversion, the threshold matrices in Figures 7.2a and b with uniform spacing between the thresholds could be used straightforwardly. However, beside the additional cost, this would add to the complexity of the hardware.

Instead we have implemented the conversion directly in the threshold matrix, resulting in an exponential conversion matrix. The numerically successive thresholds are still located in the same places as before in the dither and digital halftone matrices, respectively. However, the threshold values are now positioned across the quantization range following the exponential function in eq. (18). The actual thresholds were calculated using the following strategy: Densitometer measurements have confirmed that the maximum reflection density (black) that can be achieved in a reproduction using the composite of all three colors as black is 1.06. This is not high enough density to reproduce most photographic originals exactly, as they often contain densities of 1.8 or even higher. Therefore, most originals have to be compressed into the density range which can be generated by the plotter. We have subjectively found that if the thresholds in the exponential conversion matrix are

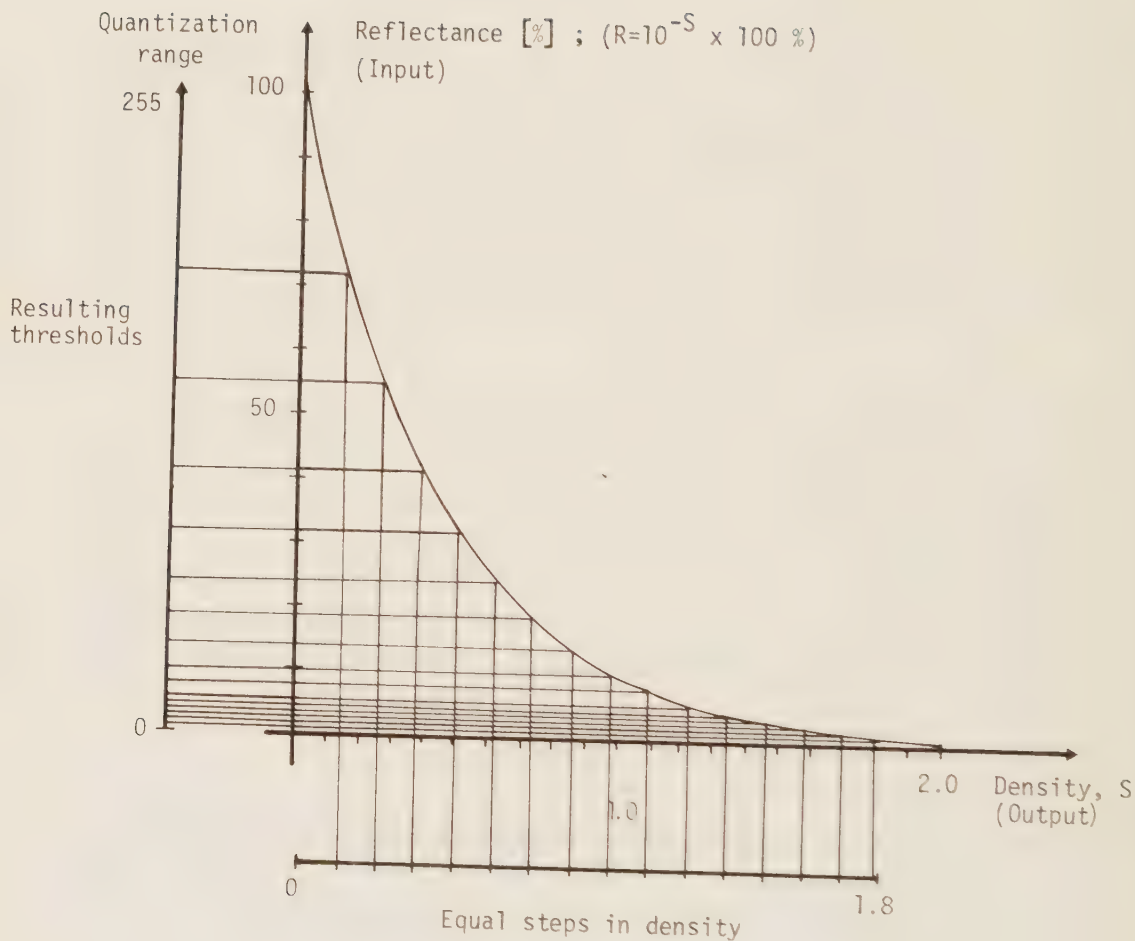


Figure 7.1. A graphical description of eq. (19). The diagram depicts how the thresholds in an exponential threshold conversion matrix are selected to give equal steps in output reflection density.

a)

240	112	208	80
48	176	16	144
192	64	224	96
0	128	32	160

b)

144	128	112	96
160	240	224	80
176	192	208	64
0	16	32	48

c)

197	25	117	15
9	70	5	42
90	11	152	19
4	32	7	54

d)

42	32	25	19
54	197	152	15
70	90	117	11
4	5	7	9

Figure 7.2. 4 x 4 threshold matrices

- (a) a linear ordered dither threshold matrix
- (b) a linear digital halftone threshold matrix
- (c) an exponential conversion ordered dither threshold matrix
- (d) an exponential conversion digital halftone threshold matrix

selected as if the original contained a density range of 0 - 1.8, the resulting reproduction comes out well. Hence, the thresholds for the quantization range of 0 - 255, where 255 corresponds to minimum density, were calculated using the following equation:

$$T_k = 10^{-\frac{(k+1)1.8}{N}} \times 255 \quad (19)$$

where T_k are numerically successive threshold values in the matrix ($k = 0, 1, 2, \dots, N$)

and N is the total number of thresholds (depending on the matrix size). For a 4 x 4 matrix this will correspond to threshold steps with an 0.113 density separation (cf. Figure 7.1). The resulting dither and digital halftone threshold matrices are shown in Figure 7.2c and d, respectively.

1.4 Experimental procedure

In this chapter we will consider only halftone reproductions of black and white images. Also, all the results shown in the figures are actually plotted with magenta ink, although different color filters were used in front of the detectors.

Since we only plotted the results with one color in these experiments, we used a special scanner/plotter arrangement that allowed simultaneous scanning and plotting on the same drum (cf. Figure 7.3). The signal from the scanner head detector was passed through the A/D-converter and the threshold matrix logic, and thereafter directly fed to the control logic of the magenta ink jet device. Thus, no intermediate storage on magnetic tape was necessary. However, the data from all the color channels were also simultaneously stored on a magnetic tape for documentation purposes.

1.5 Description of test patterns

All measurements and evaluations used the IEEE Std 167A-1980 Facsimile Test Chart, shown in Figure 7.4 and a Kodak Photographic Gray Scale, shown in Figure 7.5.

The reversed gray scale on the IEEE test chart (marked # 1 in the fi-

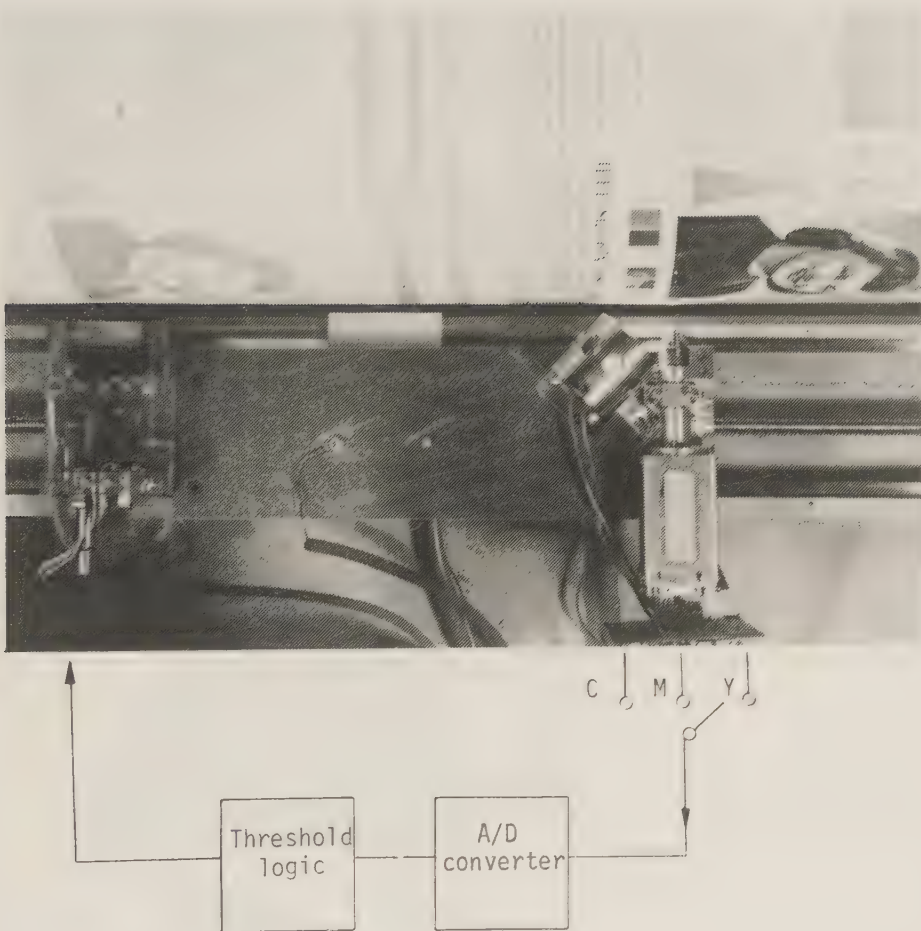


Figure 7.3. The special scanner/plotter arrangement used in the one color experiments.



Figure 7.4. The IEEE Std 167a-1980 Facsimile Test Chart

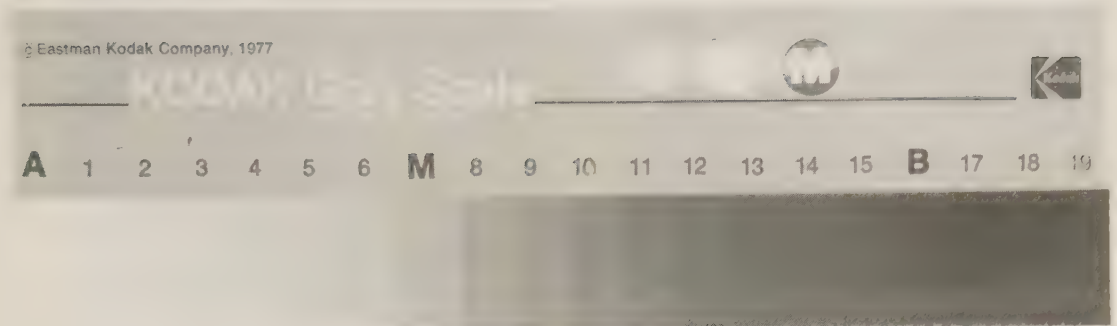


Figure 7.5. The Kodak Photographic Gray Scale with 0.1 density increments.

gure) and the Kodak Gray Scale were used for both a subjective evaluation and the densitometer measurements. The gray scale on the IEEE test chart is constructed of 15 steps with reflection densities corresponding to an approximately equal perceptibility and has a relative density range of 0 - 1.8 (referenced to the surrounding white paper). The Kodak Gray Scale is constructed of 20 density steps with density increments of 0.1 between 0 - 1.9 (referenced to the white on the scale).

The photograph of the girl was used for subjective evaluations only. The photograph is designed to show detail in both the highlight and shadow areas. The limiting densities of the photograph approximate those of the gray scale # 1.

7.6 Results

The IEEE Facsimile Test Chart was scanned and converted to a binary reproduction using both the linear and the exponential conversion 4 x 4 threshold matrices. Both ordered dither and digital halftone threshold matrices were used for comparison. The linear threshold matrices were those shown in Figures 7.2a and 7.2b, respectively, and the exponential conversion matrices were the ones shown in Figures 7.2c and 7.2d, respectively.

A subjective comparison of the reproductions of the photograph of the girl shows clearly the difference between the linear and the exponential versions of the matrices (cf. Figure 7.6a and b). Using a linear threshold matrix results in an overall darkening of the reproduction with almost no detail in the higher density regions. The reproduction using the exponential conversion matrices, on the other hand, gives a much better subjective impression with much detail even in high density areas (cf. Figure 7.7a and b).

The differences between the two reproductions using the exponential conversion in ordered dither (cf. Figure 7.7a) and digital halftone matrices (cf. Figure 7.7b), respectively, are more difficult to judge, and may differ from person to person. However, we believe that the



a



b

Figure 7.6. Reproductions of the girl photograph using linear threshold matrices: (a) the 4 x 4 ordered dither matrix in Figure 7.2a. (b) the digital half-tone matrix in Figure 7.2b.



a



b

Figure 7.7. Reproductions of the girl photograph using exponential conversion threshold matrices: (a) the 4 x 4 ordered dither matrix in Figure 7.2c. (b) the 4 x 4 digital halftone matrix in Figure 7.2d.

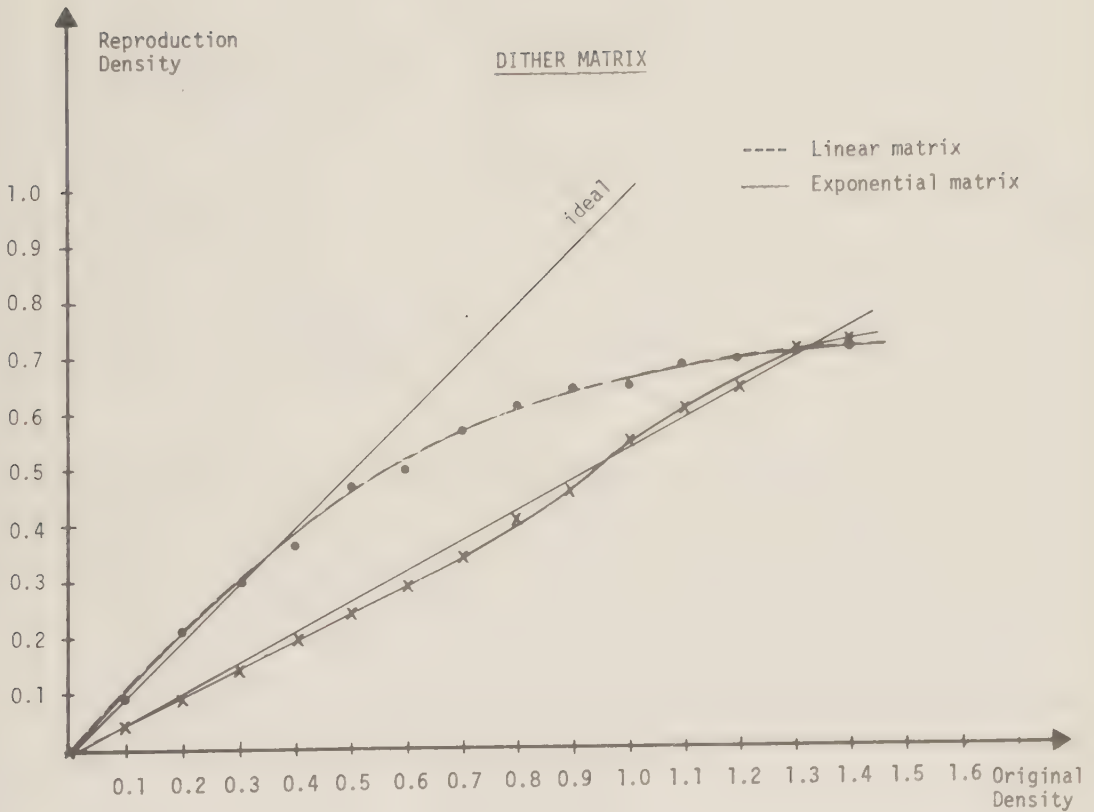


Figure 7.8. Densitometer measurement results from reproductions of the Kodak Paper Gray Scale created using the 4 x 4 linear and the 4 x 4 exponential conversion ordered dither threshold matrices in Figure 7.2a and c, respectively. The results are plotted as a function of the reflection density of the original.

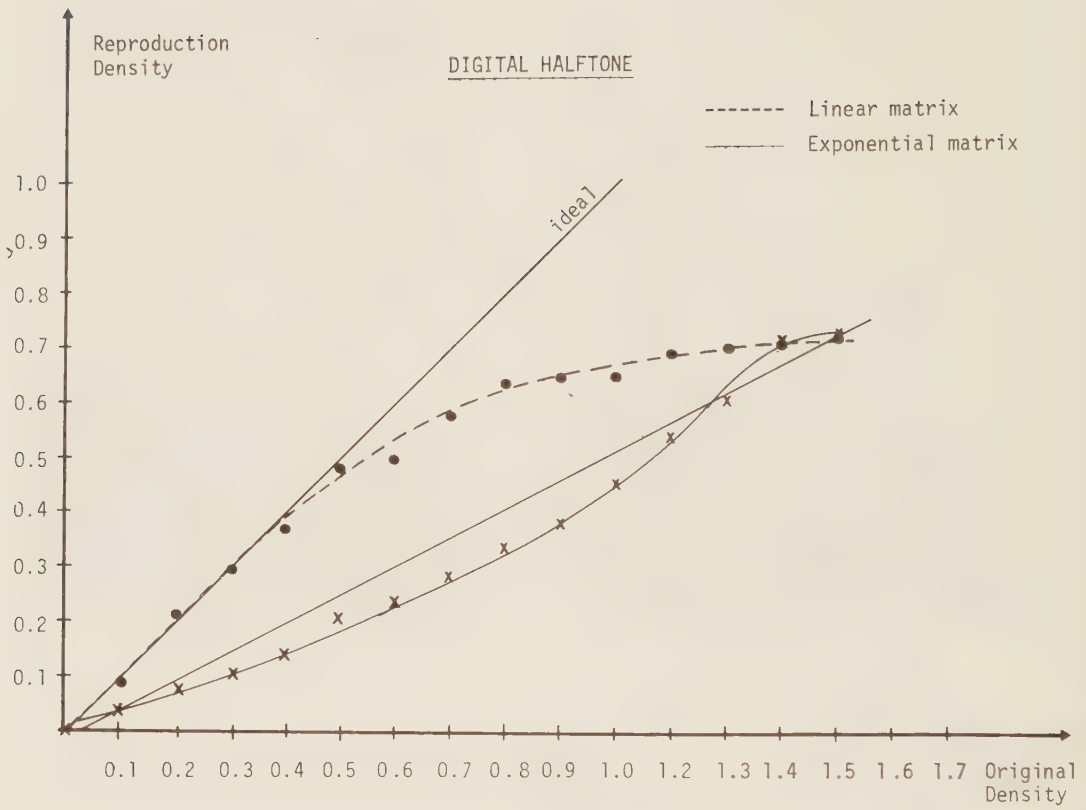


Figure 7.9. Densitometer measurement results from reproductions of the Kodak Paper Gray Scale created using the 4 x 4 linear and the 4 x 4 exponential digital halftone threshold matrices in Figure 7.2b and d, respectively. The results are plotted as a function of the reflection density of the original.

that the dithered result contains more detail than the digital halftone version.

Densitometer measurements of the gray scale reproductions are shown in Figure 7.8 and 7.9. The diagrams contain densitometer readings from both linear and exponential conversion matrix results and each data point represents the mean value of three measurements. All measurements are plotted as a function of the corresponding reflection densities in the original photograph. For reference, each diagram also contains a 45 degree line depicting an ideal reproduction. Both diagrams clearly show that the reproductions on the Ink Jet Plotter do not have as high a density as the original. This is mostly an artifact due to our non-ideal inks, but reflections on the paper surface also contribute to the error (Yule 1967). Also, the diagrams very clearly depict the logarithmic shape of the uncompensated reproductions.

The mean density value from the reproductions produced with the dither exponential conversion matrix follow very well a linear function. However, the reproduction produced with the digital halftone exponential conversion matrix shows a tendency to be overcompensated. This is due to the fact that equation (19) is derived using the characteristics of the dither patterns in chapter 5. When the same compensations is used in the digital halftone matrix an overcompensation could be predicted due to the difference in characteristics between the digital halftone and the dither patterns. This was shown earlier in chapter 5.

7.7 Conclusion

We have shown that a reflectance value in a source image can be converted to its corresponding density value in a reproduction by means of a conversion implemented directly in the threshold matrix. The obvious advantages of this solution, compared to a hardware solution using an exponential (antilogarithmic) amplifier, are low cost and its simplicity. Both subjective evaluation and measurements show that using a suitable conversion matrix results in a good reproduction with preserved detail in both low and high lightness region.

8 LIGHTNESS AND CONTRAST CONTROL

8.1 Introduction

A desirable feature of any scanner/plotter system would be the ability to control the overall lightness and contrast of the reproduced image. "Lightness control" refers to the attribute of visual perception by which an area appears to emit more or less light. "Contrast control" refers to the subjective appraisal of the relative difference in lightness between light and dark regions of reproduction.

For example, increasing the contrast in a reproduction makes the light regions appear lighter and the dark regions appear darker. Decreasing the contrast has the opposite effect, resulting in a reproduction with less perceivable differences in lightness between the lightest and the darkest regions.

Manipulations with the levels of lightness and contrast in a reproduction often give a more pleasing result.

8.2 Threshold variations providing lightness and contrast control

In a cathode ray tube system the desired level of lightness (brightness) and contrast are provided by shifting bias and amplitudes of the video signal, respectively. The electronic amplifiers in the scanner head electronics include similar control facilities in the form of an input balance control and a gain control (Nilsson 1981). However, due to the exponential conversion of the input signal described in the previous chapter, the linear changes in the analog signal do not correspond to linear changes of lightness and contrast in the pseudo-gray scale reproduction. Instead a similar effect can best be simulated by appropriate modification of the threshold in the dither threshold matrix. In particular varying the mean or average distribution of the thresholds specified by any particular algorithm changes the overall lightness, while varying the deviation or the average separation between numerically successive thresholds changes the contrast (Judice 1976a).

Without the exponential conversion built into the matrix these modifications can be expressed as

$$T'_{xy} = \sigma \left(T_{xy} - \frac{I_{\max}}{2} \right) + m \quad (20)$$

where T_{xy} is the threshold assigned to the (xy) th pixel according to the algorithm described by eq. (11) (chapter 2), T'_{xy} is the corresponding modified threshold and $I_{\max}$ is the maximum intensity. As will be shown below the σ and the m control the contrast and lightness, respectively. In particular $\sigma = 1$ and $m = \frac{I_{\max}}{2}$ replicates the original thresholds. Decreasing σ ($0 < \sigma < 1$) increases the contrast while increasing σ ($\sigma > 1$) decreases the contrast. Similarly, decreasing m increases the lightness and vice versa. Also $\sigma = 0$ corresponds to a single threshold with the value equal to m throughout the matrix.

An illustration of the principles of pseudo-gray scale lightness and contrast control in case of a linear ordered dither matrix is shown in Figure 8.1. Matrix D^{16} (cf. Figure 8.1a) is a conventional linear 4×4 dither matrix for the quantization range 0 - 255, where 255 represents maximum intensity. Now, if $\sigma = 1$ and $m = \frac{I_{\max}}{2} + 32$ and equation (20) is used we derive the threshold matrix $|D^{16}|'$

$$|D^{16}|' = D^{16} + 32 \quad (21)$$

As the mean of the thresholds has been increased by 32, each threshold in $|D^{16}|'$ is 32 units larger than the corresponding threshold of matrix D^{16} (cf. Figure 8.1b). Therefore, on the average, fewer pixel intensities throughout the source image exceed their assigned threshold. This will result in a decrease in the overall lightness in the reproduction. Analogously, decreasing the mean of the thresholds ($m < \frac{I_{\max}}{2}$) will result in an overall lighter reproduction.

With $\sigma = 0.5$ and $m = \frac{I_{\max}}{2} = 128$ we will derive the matrix $|D^{16}|''$ as follows

$$|D^{16}|'' = 0.5 D^{16} + 64 \quad (22)$$

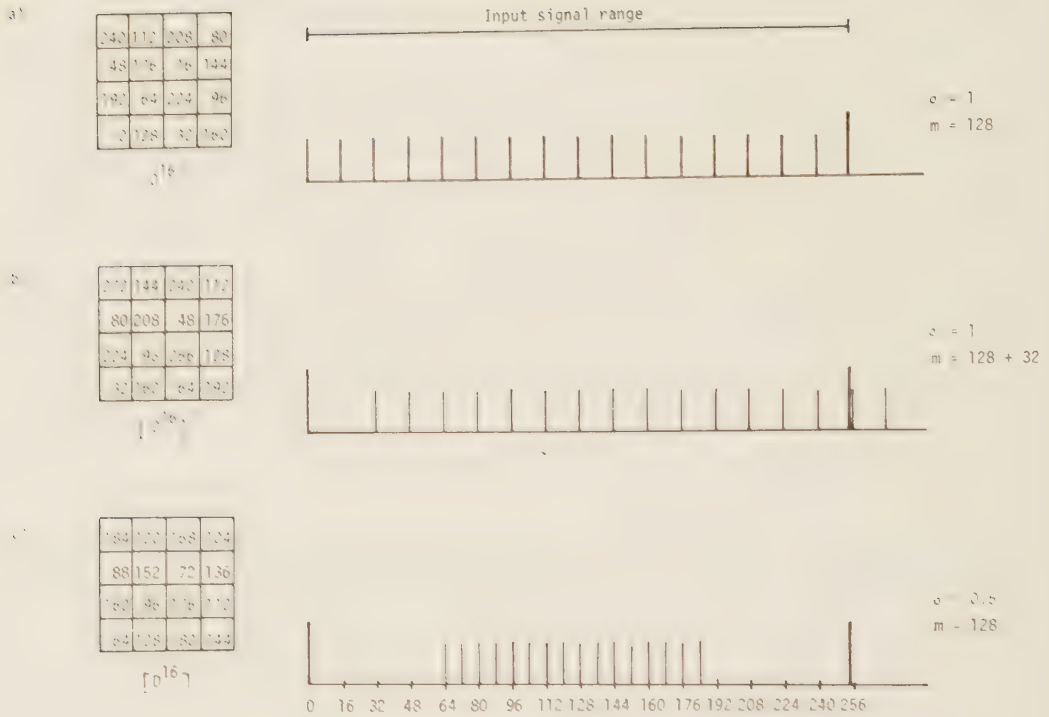


Figure 8.1. Modifications of the linear ordered dither threshold matrix (D^{16}) to achieve contrast and lightness control. The σ and m values control contrast and lightness, respectively.

(a) $\sigma = 1$ and $m = 128$ replicates the original (D^{16}) thresholds.

(b) An increase of m ($m > 128$) decreases the lightness and vice versa.

(c) A decrease in σ ($0 < \sigma < 1$) increases the contrast; while $\sigma > 1$ decreases the contrast.

Now the deviation of the numerically successive thresholds is 8, as compared to the 16 for the threshold of D^{16} (cf. Figure 8.1c). Thus, in the dark regions of the source image fewer pixel intensities will exceed their assigned thresholds, on the average, and therefore the corresponding regions in the reproduction will appear darker. At the same time, more pixels in the relatively light regions of the source image will, on the average, exceed their assigned threshold and, therefore, the corresponding areas in the reproduction will appear much lighter. In this way the combination of the dark regions in the reproduction being darkened and the light regions being lighter provides an overall increase in the contrast of the reproduction.

8.3 Modification of the conversion matrix to implement lightness and contrast control

Equation (20) does not apply straightforwardly for the thresholds in the exponential conversion matrix derived in chapter 6. However, the same principle can be applied to the equation used for calculating those thresholds (Eq. (19) in chapter 7). One has only to remember that the thresholds are calculated to represent linear steps in density, before they are converted to their corresponding value of reflectance (cf. chapter 7). Therefore, the m and σ have to correct the mean and deviation in density.

Thus, equation (19) in chapter 7 has to be modified to include contrast and lightness control in a density range of 0 - 1.8. Combining eq. (19) and (20) and assuming a maximum density $S_{\max} = 1.8$ we get

$$T'_k = 10^{\sigma \left(- \frac{(k+1) \cdot 1.8}{N} + \frac{1.8}{2} \right) - m} \times 255 \quad (23)$$

where T'_k are numerically successive threshold values in the matrix ($k = 0, 1, 2, \dots, 15$)
 N is the total number of thresholds in the matrix
 σ contrast control factor
 m lightness control factor

As before, $\sigma = 1$ and $m = \frac{1.8}{2} = 0.9 (= \frac{S_{\max}}{2})$ replicates the original

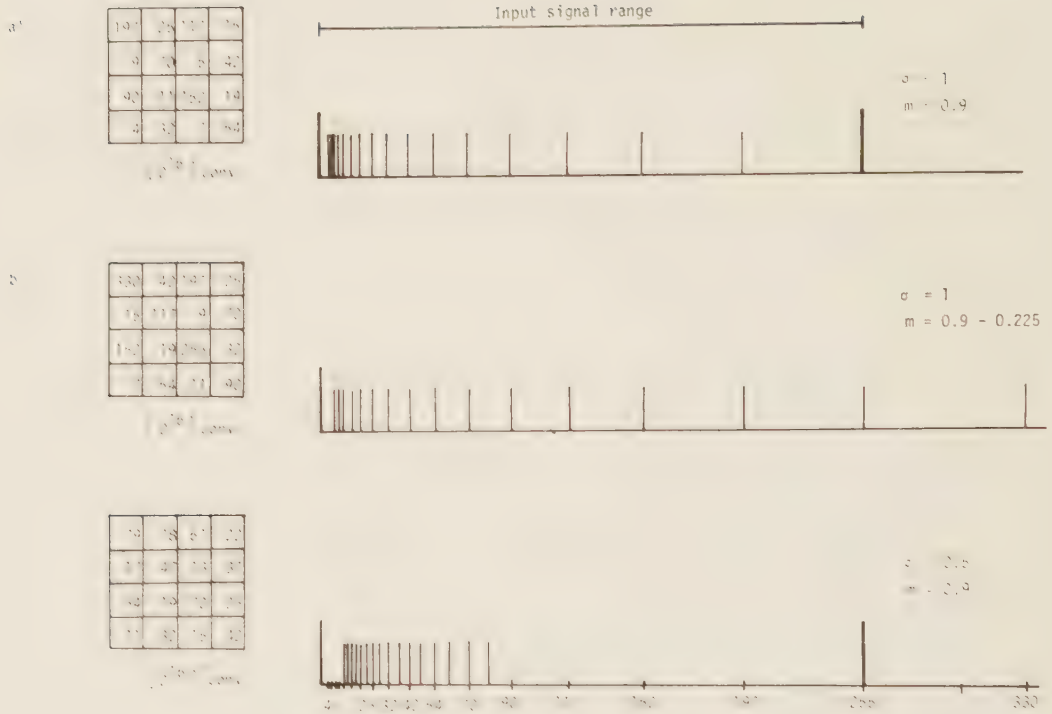


Figure 8.2. Modifications of the exponential conversion ordered dither threshold matrix ($|D^{16}|_{\text{conv}}$) to achieve contrast and lightness control. The σ and m values control contrast and lightness, respectively.

(a) $\sigma = 1$ and $m = 0.0$ replicates the original ($|D^{16}|_{\text{conv}}$) thresholds.

(b) A decrease in m ($m < 0.9$) will decrease the lightness and vice versa.

(c) A decrease in σ ($0 < \sigma < 1$) increases the contrast, while $\sigma > 1$ decreases the contrast.

thresholds of the experimental conversion matrix (cf. Figure 8.2a). Now, variations of the σ and m factors will have similar effects on the contrast and lightness of the reproduction as was shown in the previous section.

Especially, setting $\sigma = 1$ and $m = 0.9 - 0.255$ results in the thresholds shown in Figure 8.2.b. These thresholds correspond to the $m = \frac{S_{\max}}{2} + 32$ for the linear distribution and will therefore result in and overall decrease in lightness of the reproduction.

In the same way $\sigma = 0.5$ and $m = 0.9$ results in the thresholds shown in Figure 8.2c and corresponds to the $\sigma = 0.5$ and $m = \frac{S_{\max}}{2}$ mentioned earlier and thus results in an increase in contrast of the reproduction.

8.4 Results

The photograph of the girl on the IEEE Facsimile Test Chart (shown earlier, cf. Figure 7.4) was used as a source image to verify the effects of lightness and contrast control using different threshold matrices.

The photograph was scanned using the exponential conversion matrix with ordered dither thresholds, and different σ and m factors.

Figure 8.3 shows the reproduction with $\sigma = 1$ and $m = 0.9$, i.e. with normal lightness and contrast.

If σ was kept equal to 1 but m was changed to $m = 0.9 - 0.225$ the decrease in lightness expected is clearly visible in the reproduction (cf. Figure 8.4a). A change of m to $m = 0.9 + 0.225$ still with $\sigma = 1$ gives the opposite effect as shown as an overall increase in the reproduction lightness (cf. Figure 8.4b).

Finally σ was set to 0.5 keeping m at the normal level of 0.9. Now the reproduction showed the expected large increase in contrast (cf. Figure 8.5a). A more moderate increase in contrast was achieved with a σ of 0.75 (m still equal to 0.9) as shown in Figure 8.5b.



Figure 8.3. The IEEE girl photograph reproduced with $\sigma = 1$ and $m = 0.9$, i.e. the normal exponential conversion ordered dither threshold matrix.



a



b

Figure 8.4. Lightness control due to changes in the m factor while σ is kept constant:
 (a) $m = 0.9 - 0.225$ ($\sigma = 1$) decreases the lightness, while
 (b) $m = 0.9 + 0.225$ ($\sigma = 1$) increases the lightness
 when compared to the reproduction in Figure 8.3.

Here we have only considered variations in either leightness or contrast, but a combination of changes in both factors can of course also be used.



a

b

Figure 8.5. Contrast control due to changes in the factor, while m is kept constant:
 (a) $\sigma = 0.5$ ($m = 0.9$) drastically increases the contrast, while
 (b) $\sigma = 0.75$ ($m = 0.9$) results in a more moderate increase in contrast when compared to the reproduction in Figure 8.3.

9 MATRIX SIZE CONSIDERATIONS

9.1 Introduction

The size of the threshold matrix determines the number of obtainable pseudo-gray levels in a reproduction. Typically, an $n \times n$ size matrix can simulate $n^2 + 1$ levels of gray. However, there are often practical limits to the choice of matrix size, such as loss in spatial resolution in the reproduction with increasing matrix size, hardware considerations and the noise level of the intensity input signal.

The physical size of a dither matrix generated by a 4×4 threshold matrix is $0.8 \times 0.8 \text{ mm}^2$. Now, if the threshold matrix is increased to 8×8 thresholds, this will correspond to an area of $1.6 \times 1.6 \text{ mm}^2$. The large physical size of the matrix must influence the quality that can be obtained, especially in high detail areas. Judice et al. (1974) have shown that the errors in the simulated gray levels in the reproduction increase when the detail of the source image approaches the matrix size.

The structure of the ordered dither matrix minimizes the effects of resolution losses when the matrix size is increased. The 8×8 threshold matrix is built from smaller matrices in a gradual way (see eq. (8) and (11)), so that the ability to reproduce detail gradients is only weakly dependent on the matrix size. A larger matrix will have no loss of spatial resolution in high contrast detail, but a gradually degrading resolution for lower contrast regions. The effects of this will be demonstrated in section 9.3.

The structure of the digital halftone matrix, on the other hand, does not lend itself to such large matrices as $1.6 \times 1.6 \text{ mm}^2$ without a substantial loss in resolution as will be shown below.

9.2 The construction of an 8×8 exponential conversion threshold matrix

The construction of an 8×8 threshold matrix would be straightforward if no exponential conversion had to be implemented using the thresholds.

Equation (11) could be used directly, and the threshold would have linearly consecutive steps of 4 levels.

An 8×8 exponential conversion matrix is calculated using equation (19) with $N = 64$. The resulting thresholds are shown in Figure 9.1. A problem arises as many of the low thresholds will have the same value. This cannot be accepted, because it will result in visible patterns in the reproductions (cf. Figure 9.2). The solution to this problem was to adjust the lower thresholds so that they all had different values. This resulted in an overall upward adjustment of all the other thresholds, without changing the consecutive differences of those thresholds. The resulting 8×8 ordered dither matrix and digital halftone matrix are shown in Figure 9.3a and b, respectively.

The noise level of the input intensity signal corresponds to between 4 and 6 quantization levels, as shown in table 6.1. This implies that the difference between two consecutive thresholds should always be larger than 4 steps. Smaller gray level differences in the source image cannot be distinguished anyway due to the noise. However, we have found that our reproductions show differences that correspond to 1 and 2 quantization steps. Even though this is a form of noise level in reproduction, it gives a subjectively more pleasing result than if we used threshold steps always larger than 4. Larger steps between the lower thresholds will result in a substantial loss of detail in the dark regions of the reproduction.

9.3 Comparison of reproductions using 8×8 and 4×4 threshold matrices

The IEEE Facsimile Test Chart (cf. Figure 7.4) was used to evaluate the differences between the 4×4 and 8×8 threshold matrices. The photograph of the girl was, as before, used to evaluate the gray scale differences, but also to visualize low contrast spatial resolution differences. The resolution patterns were used to show the effects in high contrast regions with variations in matrix size and threshold algorithms.

The tested 8×8 ordered dither and digital halftone threshold matrices

4	32	7	54	5	37	8	61
90	11	152	19	103	13	173	22
9	70	5	42	10	79	6	47
197	25	117	15	224	28	133	17
5	39	8	65	4	34	7	57
110	14	184	23	97	12	162	20
11	85	6	51	9	75	6	44
239	30	142	18	210	26	125	16

Figure 9.1. Exponential conversion implemented in an 8 x 8 ordered dither threshold matrix. The thresholds are calculated from Eq. (19). The matrix contains many equal low value thresholds.



Figure 9.2. The result of using the 8 x 8 threshold matrix in Figure 9.1. The matrix contains many equal low value thresholds, and that results in unacceptable white patterns in the reproduction.

250	35	151	23	221	31	134	21
15	93	7	56	13	83	5	49
119	19	195	27	106	17	172	25
3	44	11	72	1	39	9	62
208	29	126	20	235	33	142	22
12	77	4	47	14	87	6	52
99	16	162	24	112	18	184	26
0	37	8	59	2	42	10	67

A.

21	20	19	18	17	16	15	14
22	72	67	62	59	56	52	13
23	77	172	162	151	142	49	12
24	83	184	250	235	134	47	11
25	87	195	208	221	126	44	10
26	93	99	106	112	119	42	9
27	29	31	33	35	37	39	8
0	1	2	3	4	5	6	7

B.

Figure 9.3. Exponential conversion 8 x 8 threshold matrices adjusted to contain no equal threshold values
 (a) ordered dither thresholds
 (b) digital halftone thresholds.

are shown in Figure 9.3a and b, respectively, and the 4 x 4 ordered dither and digital halftone threshold matrices are shown earlier in Figure 7.2c and d, respectively.

All the reproductions are plotted using the magenta ink and at a drum surface speed of 3.5 m/s.

Figure 9.4a shows the 8 x 8 dither matrix reproduction. The girl photograph contains much less contouring effects than the 4 x 4 dither matrix reproduction shown in Figure 9.4b, without any directly visible loss in detail. However, a closer look at the girl's hair will disclose that some detail is lost in its low contrast regions.

The 4 x 4 digital halftone matrix reproduction, shown in Figure 9.5b has definitely lost detail when compared to the two dither reproductions. It also contains similar contouring effects as the 4 x 4 dither matrix reproduction.

When the digital halftone matrix is increased to contain 8 x 8 thresholds the resulting reproduction (cf. Figure 9.5a) shows an increased texture and a substantial loss in detail.

The corresponding reproductions of the text and resolution patterns are shown in Figure 9.7 and 9.8. Figure 9.6 visualizes the maximum resolution that can be achieved using the ink jet plotter and a single threshold value. This is shown to give a better feeling for how the threshold matrix algorithms influence the resolution, especially as the test pattern contains areas that can never be reproduced correctly due to the 5 lines/mm limitation of the system.

The text and the resolution patterns represent high contrast source images. Therefore, due to the basic principle of the threshold algorithms, only minor differences should be seen when the threshold matrices are changed. Relatively high intensity and relatively low intensity regions in a source image will always result in "pure white" and "pure black" in the reproduction.



a



b

Figure 9.4. Reproductions of the IÉEE girl photograph using ordered dither threshold matrices:
(a) the 8 x 8 threshold matrix in Figure 9.3a.
(b) the 4 x 4 threshold matrix in Figure 7.2c.



a



b

Figure 9.5. Reproductions of the IEEE girl photograph using digital halftone threshold matrices:
(a) the 8 x 8 threshold matrix in Figure 9.3b.
(b) the 4 x 4 threshold matrix in Figure 7.2d.

This is also visible in Figure 9.7a and b and 9.8a and b. Although the threshold algorithms and the matrix sizes are varied, the high contrast regions do not show any large differences, as was the case for the relatively low contrast regions in the girl photograph.

9.4 Conclusions

From these experiments it can be concluded that the choice of threshold matrix size is application dependent. In an application where the source image contains details that are smaller than or comparable to the size of the threshold matrix ($0.8 \times 0.8 \text{ mm}^2$ for a 4×4 matrix and $1.6 \times 1.6 \text{ mm}^2$ for an 8×8 matrix) the ordered dither threshold matrix results in a higher resolution than the digital halftone threshold matrix. Therefore, in all our applications the choice has been to use a 4×4 or an 8×8 dither threshold matrix.

Whenever the source image contains low contrast detail the 4×4 threshold matrix is preferable to the larger 8×8 matrix. Only when many gray levels have to be reproduced the 8×8 dither matrix should be used. When a source image contains both high detail and low contrast regions as well as many gray levels, the choice of matrix size is a trade-off between detail and the number of gray-levels in the reproduction.

FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 8 pt

FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 10 pt

FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 12 pt

IEEE Std 167A-1980

FACSIMILE TEST CHART

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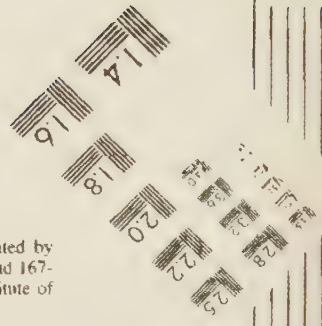


Figure 9.6. A single threshold (= 128) reproduction of the text and resolution patterns in the IEEE Facsimile Test Chart shown in Figure 7.4. This visualizes the maximum resolution that can be obtained using the scanner/plotter system.

FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 8 pt

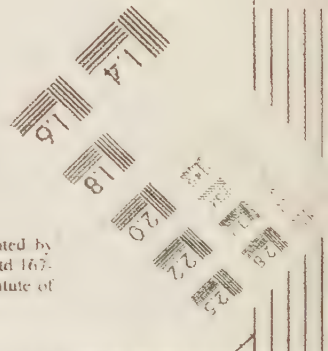
FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 10 pt

FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 12 pt

IEEE Std 167A-1980

FACSIMILE TEST CHART

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FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 8 pt

FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 10 pt

FGHIJKLMNOPQRSTUVWXYZ
 fghijklmnopqrstuvwxyz
 567890 Spartan Medium 12 pt

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FACSIMILE TEST CHART

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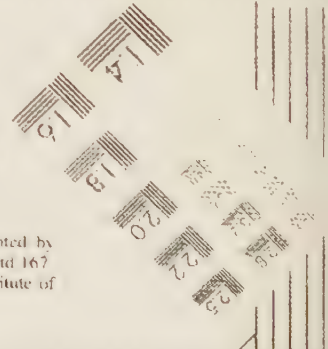


Figure 9.7. Reproductions of the text and resolution patterns in the IEEE Facsimile Test Chart using ordered dither threshold matrices:
 (a) the 8 x 8 threshold matrix in Figure 9.3a.
 (b) the 4 x 4 threshold matrix in Figure 7.2c.

ABCDEF GHIJKLMNOPQRSTUVWXYZ
 abcdefghijklmnopqrstuvwxyz
 1234567890 Spartan Medium 8 pt

a

IEEE Std 167A-1980

FACSIMILE TEST CHART

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ABCDEF GHIJKLMNOPQRSTUVWXYZ
 abcdefghijklmnopqrstuvwxyz
 1234567890 Spartan Medium 10 pt

ABCDEF GHIJKLMNOPQRSTUVWXYZ
 abcdefghijklmnopqrstuvwxyz
 1234567890 Spartan Medium 12 pt

ABCDEF GHIJKLMNOPQRSTUVWXYZ
 abcdefghijklmnopqrstuvwxyz
 1234567890 Spartan Medium 8 pt

b

IEEE Std 167A-1980

FACSIMILE TEST CHART

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ABCDEF GHIJKLMNOPQRSTUVWXYZ
 abcdefghijklmnopqrstuvwxyz
 1234567890 Spartan Medium 10 pt

ABCDEF GHIJKLMNOPQRSTUVWXYZ
 abcdefghijklmnopqrstuvwxyz
 1234567890 Spartan Medium 12 pt

Figure 9.8. Reproductions of the text and resolution patterns in the IEEE Facsimile Test Chart using digital halftone threshold matrices:
 (a) the 8 x 8 threshold matrix in Figure 9.3b.
 (b) the 4 x 4 threshold matrix in Figure 7.2d.

10 THE REPRODUCTION OF COLOR PICTURES

10.1 Color terminology

In order to discuss color ink jet printing a short introduction to color terminology is appropriate. More detail on the subject can be found in textbooks (Yule 1967 and Wright 1969).

The perception of color is a subjective experience in which physiological and psychological factors play an important part. Perceived color can be seen as the eye's measure and the brain's interpretation of the dominant wavelength or energy of a light wave. The meaning of this is clear in the case of monochromatic light which has a single, well-defined wavelength. However, the interpretation of light that is a mixture of many wavelengths is more complicated, but it is still the relative combinations of the various wavelengths that determine the color.

The three attributes that are most commonly used to describe the appearance of color are hue, saturation, and lightness. For convenience these attributes are often geometrically described as being parameters in a double cone (cf. Figure 10.1).

Variations in hue are represented around the circumference and correspond to the differences in wavelength, i.e. determine whether a color appears blue, green, or yellow, etc.

Saturation variations are represented along the radii, and denote the absence of a white component. Colors of increasing saturation are located at increasing distances from the axis.

Variations in lightness are represented along the axis of the cone, described as ranging from white to black, thus relating to the relative amount of reflected light.

10.2 Principles of color reproduction

10.2.1 Introduction

The human eye cannot distinguish between a color with a complex spectrum

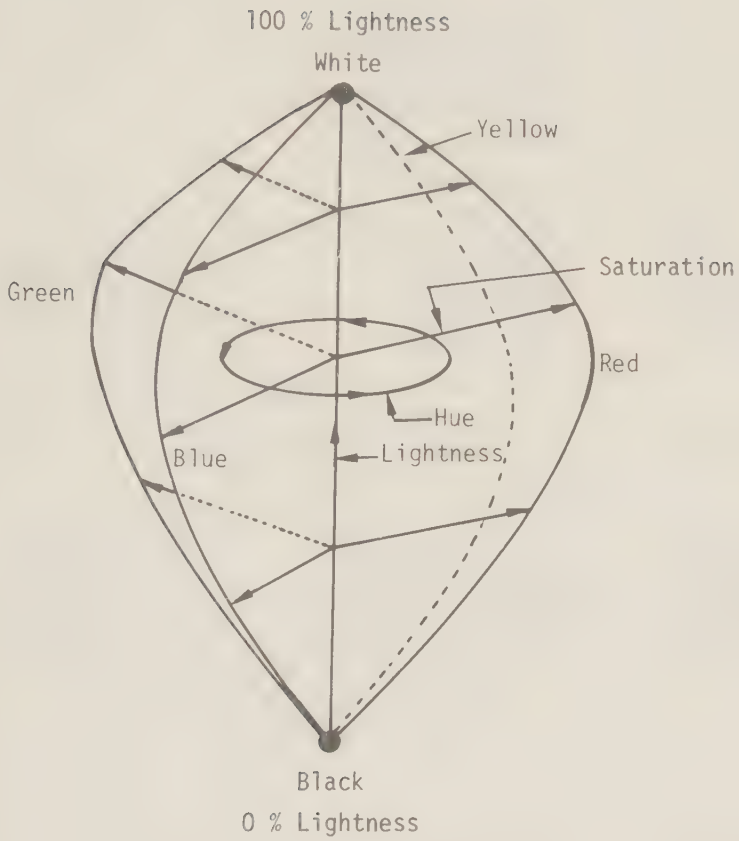


Figure 10.1. A geometrical representation of the color attributes hue, saturation and lightness.

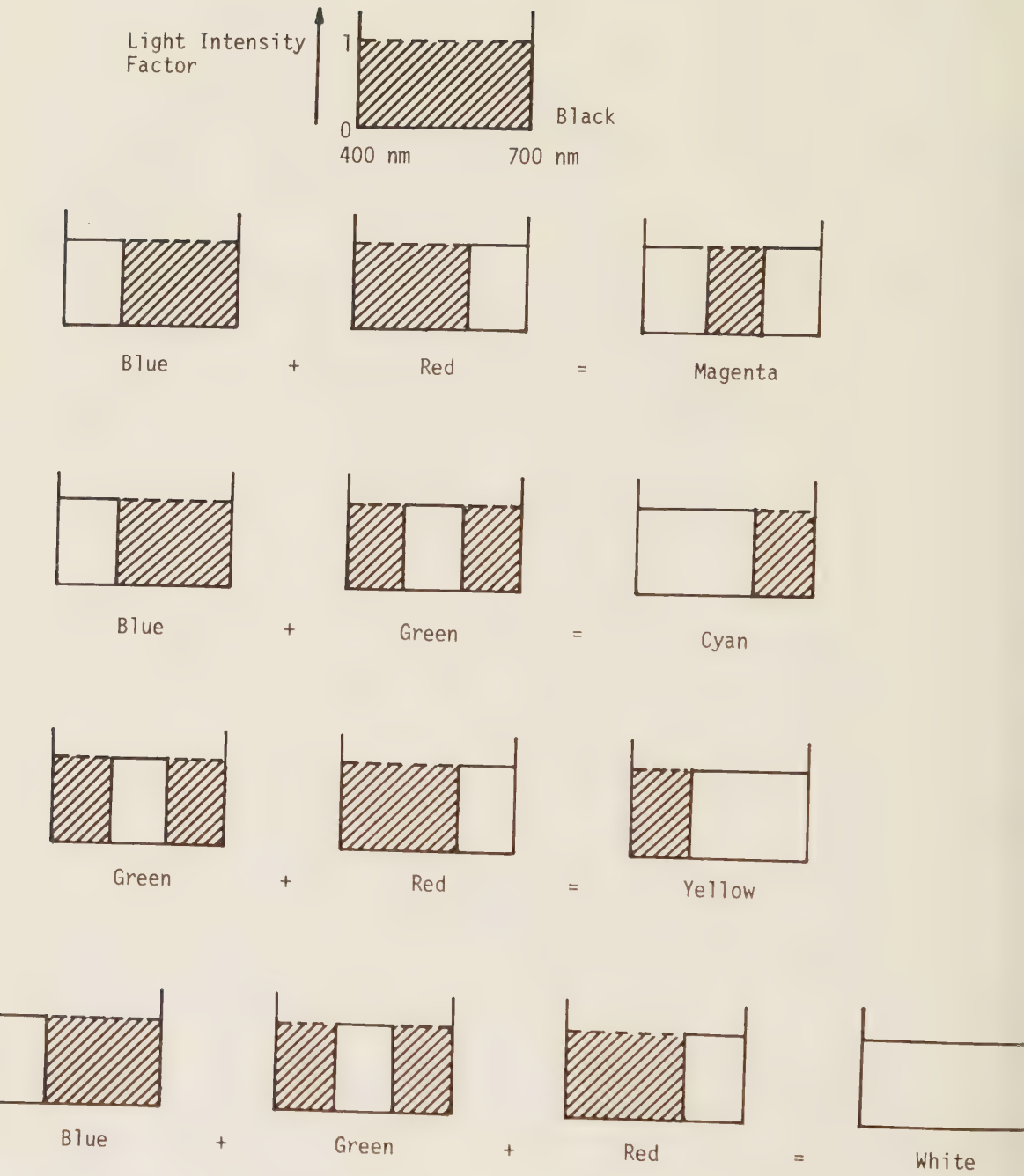


Figure 10.2. The principle of additive color mixture.

and a corresponding three color mixture. The fact is applied both in color photography and the printing of most color pictures, where all but the most saturated colors are represented by a proper mixture of a certain set of three basic colors. The three colors, called primary colors, are sometimes said to be red, green, and blue, and sometimes magenta, yellow, and cyan. Both these statements are true, but they apply to two different types of color mixtures. Much confusion about this can be avoided by making it clear whether it is colored lights or colored objects that are involved.

10.2.2 Additive color mixture

Red, green, and blue are the additive primary colors, each transmitting one third of the visible spectrum. Their wavelengths correspond well with the spectral sensitivities of the cones in the human eye.

The additive method to mix colors uses the fact that closely spaced non-overlapping dots or fields of primary colors cannot be resolved by the eye. The light transmitted from each dot will therefore be added together and result in a perceived color (cf. Figure 10.2). Changing the contributions of light transmitted from each primary colored dot will create a variety of perceived colors. A typical example of an additive color mixture is provided by the screen of a color television tube.

10.2.3 Subtractive color mixture

The subtractive primary colors magenta, yellow, and cyan are complementary colors to the additive primary colors green, blue, and red. Thus, magenta, yellow, and cyan each subtracts one third of the visible spectrum and transmits only the complementary two thirds (cf. Figure 10.3).

Subtractive color mixture is an overlapping technique. Dyes or pigments are printed on top of each other, each subtracting or absorbing its characteristic part of the spectrum. Typically, amounts of red, green, and blue are subtracted from a white reflecting (paper) substrate. This is accomplished by applying proportions of cyan, magenta, and yellow dyes which absorb red, green, and blue, respectively. This technique is used in both color photography and color printing.

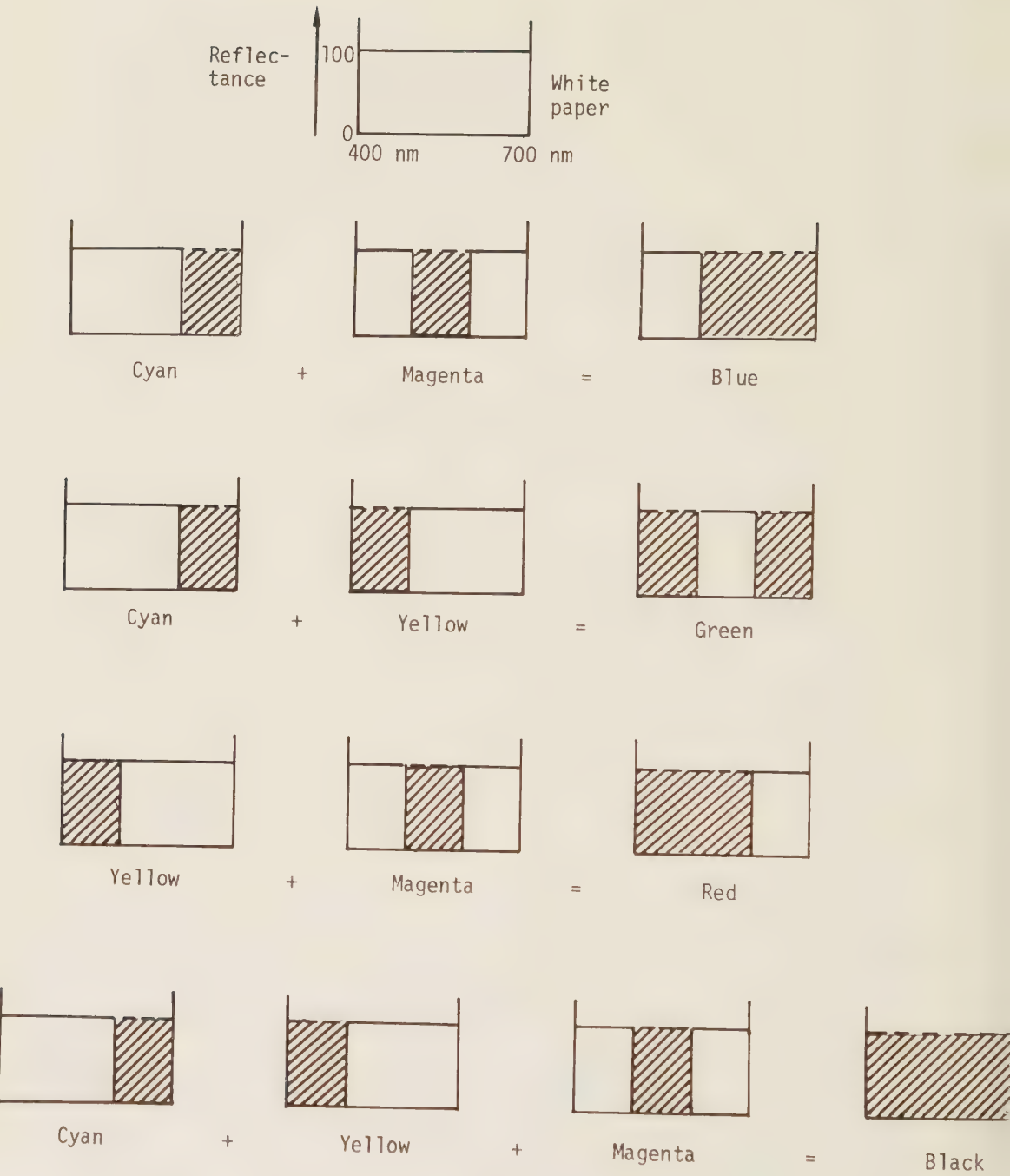


Figure 10.3. The principle of subtractive color mixture.

10.3 Creating colors using matrices

To demonstrate how a variety of composite colors can be achieved with the Ink Jet Color Plotter, consider a small white matrix composed of four elements as shown in Figure 10.4a. By covering one element of the matrix with cyan ink, one-fourth of the red reflected light is absorbed. The visual effect is a cyan hue, very light, desaturated color (cf. Figure 10.4b). If the cyan coverage is increased the hues remain the same, but saturation is increased while lightness decreases (cf. Figure 10.4c).

The addition of an equal amount of yellow and magenta will have the effect of an added black component, as shown in Figure 10.5b. This decreases the lightness but leaves the hue and the saturation unchanged.

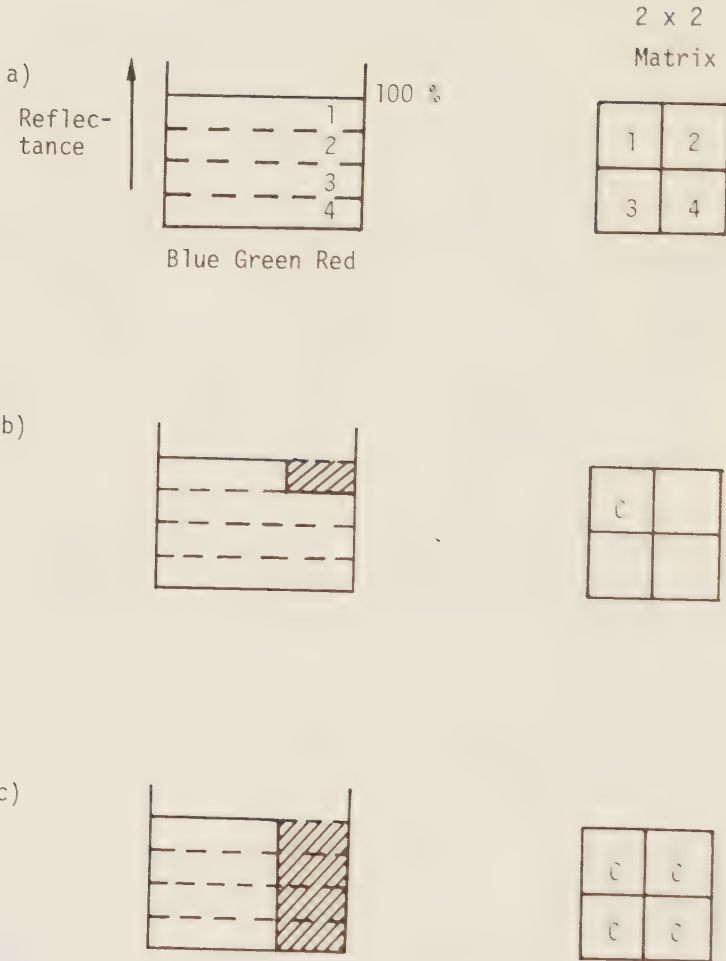
A shift in hue can be attained by adding unequal amounts of yellow and magenta. Adding more yellow than magenta will shift the result towards green (cf. Figure 10.5c).

In this simplified example a 2 x 2 element matrix has been used. Using a larger sized matrix provides the possibility of reproducing a larger variety of color combinations.

10.4 Color separation

In order to produce color reproductions, the color of each pixel in the source image must be separated into primary colors. In the scanner head this separation is achieved using a colored filter in front of the photo diode detector (Nilsson 1981). The filters are Kodak Wratten Filters K25 (red), K58 (green) and K47 (blue), having the transmission curves shown in Figure 10.6 (Kodak Filter Manual 1970).

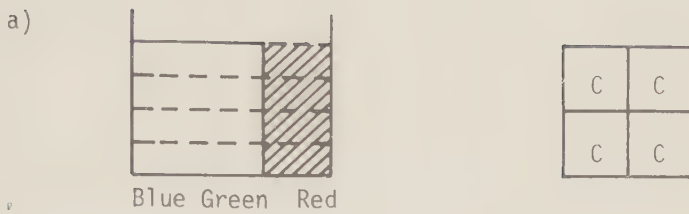
According to the definition of subtractive colors, the colored ink dye deposited on the paper serves as a non-transparent filter for light from that third of the spectrum which constitutes the complementary color to the color of the dye. Thus, for the control of an ink jet having a certain color, a filter producing the complementary color to the ink color should be used in front of the detector. To discuss a more specific



VARIATION IN SATURATION

Figure 10.4. Variation in saturation within a 2 x 2 matrix area:

- white paper with neutral hue and maximum lightness.
- one cyan ink dot in the matrix results in an impression of light cyan. Thus the hue is cyan, the lightness is high and the saturation is low.
- all four matrix elements covered by cyan ink results in an impression of saturated cyan. The hue is unchanged (cyan), the lightness is reduced and the saturation is maximum.



VARIATION IN LIGHTNESS



VARIATION IN HUE

Figure 10.5. Variation in lightness and hue within a 2 x 2 matrix area:
 (a) saturated cyan,
 (b) adding equal amounts of yellow and magenta leaves the saturation unchanged but the lightness is decreased
 (c) hue is shifted towards green when more yellow is added, leaving the saturation unchanged but further decreasing the lightness.

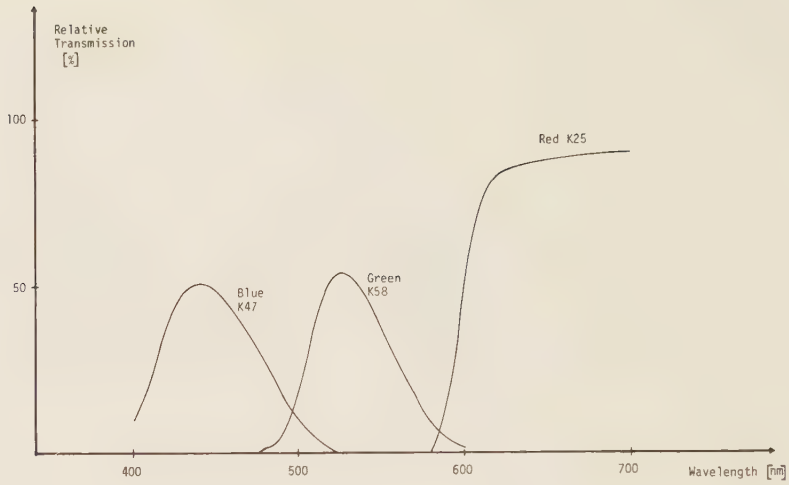


Figure 10.6. Transmission curves for the optical filters used in the scanner head and the densitometer. Kodak Wratten filters K25(red), K58 (green) and K47(blue). (Kodak Filter Manual, 1971).

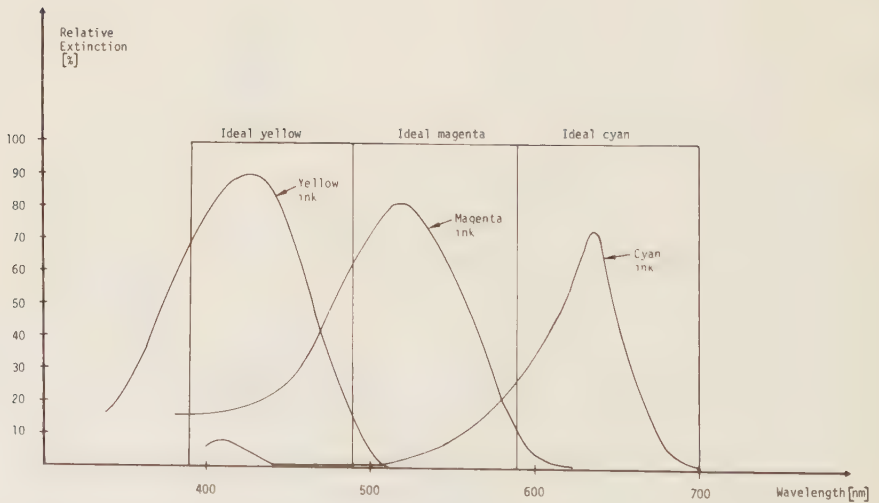


Figure 10.7. Absorption curves for ideal color inks and for the color inks used in the ink jet plotter. (Siemens-Elema AB, Solna, Sweden)

sample, let us assume that we want to control the yellow ink jet. As the amount of blue reflected from the scanned pixel is a direct measure of the amount of yellow dye in that pixel, we use a blue filter in front of the detector. A large amount of blue light reflected will therefore correspond to little or no yellow to be printed and vice versa.

The same reasoning is applied to the green/magenta printing and the red/cyan printing to obtain the same red, green, and blue reflectance in the copy as in the original.

10.5 Ideal vs. non-ideal inks

The double cone in Figure 10.1 defines the appearance of color. However, in color ink printing the number of colors that can be achieved is limited. The limitation is a function of the color attributes of the cyan, magenta, and yellow primary dyes which are used in the inks, as well as the surface of the paper upon which the inks are printed. The inks used in the experiments described below are produced by Siemens-Elcoma AB, Solna, Sweden.

Ideal inks would have sharply defined absorption bands that exactly correspond to the primary colors, as indicated in Figure 10.7. This figure also contains the absorption curves from the actual inks used in the Ink Jet Color Plotter. These curves clearly show that the inks used in the Ink Jet Color Plotter are non-ideal. All the three inks show secondary absorption in unwanted portions of the visible spectrum.

If cyan ink was a perfect absorber it would only absorb the red light. The paper would reflect blue and green light, as shown in Figure 10.8a. However, generally cyan ink absorbs red light as it should, but it also absorbs some green light and some blue light, as shown in Figure 10.8b. Thus, it acts as though it was contaminated with those inks whose function it is to absorb green and blue light, i.e. magenta and yellow ink, respectively.

If magenta ink was a perfect absorber it would absorb only the green light. The paper would reflect blue and red light, as shown in Figure 10.8c. How-

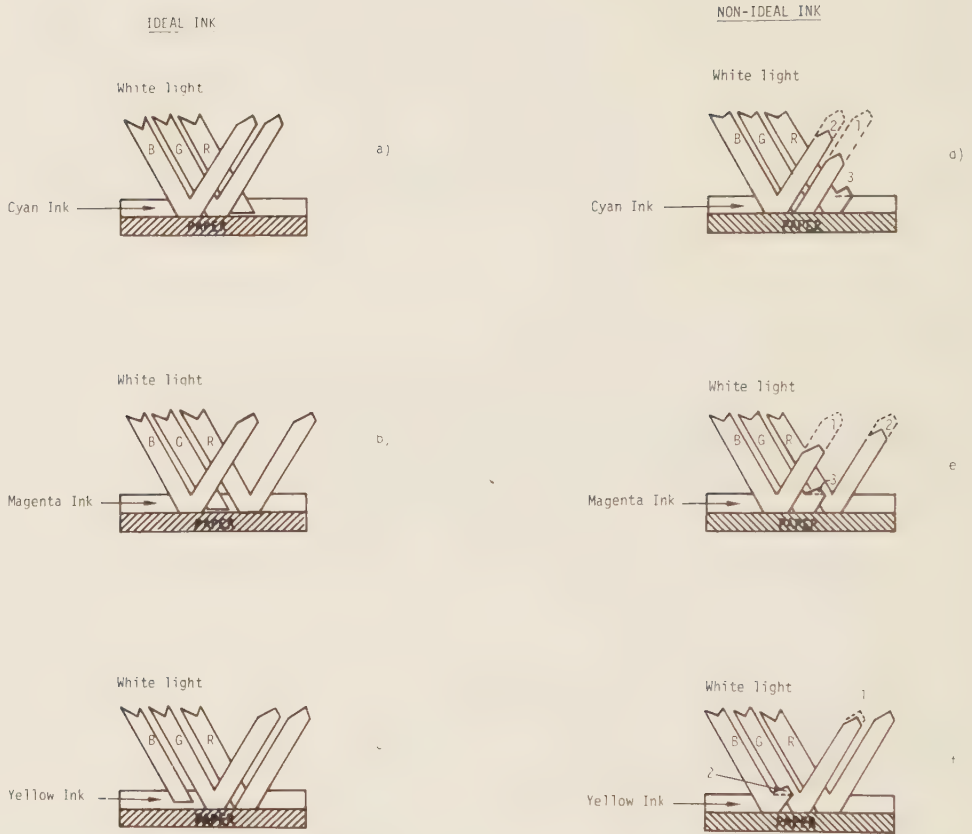


Figure 10.8. Light-absorbing action of ideal inks (a-c) and non-ideal inks (d-f).

Figure 10.9. Kodak Color Control Patches (shown on the following page)
Original (top).
Ink color reproduction using the 4 x 4 ordered dither threshold matrix shown in Figure 7.2c. (below).

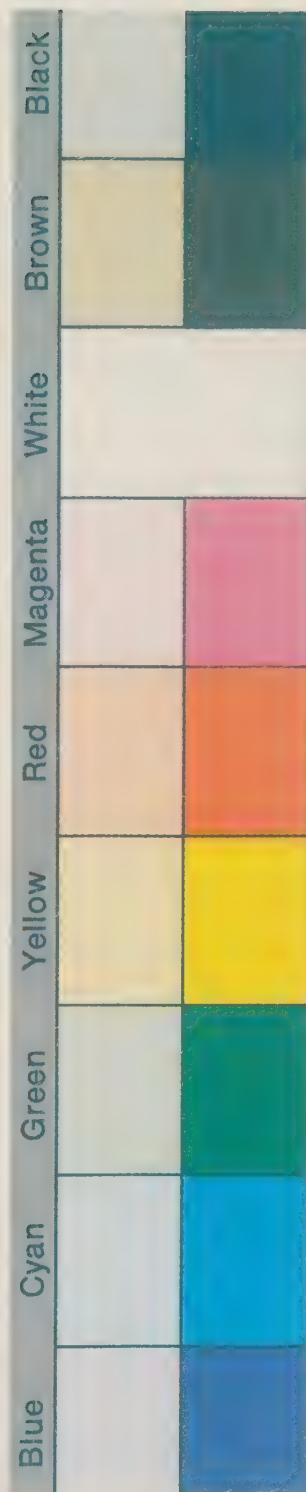
ever, the magenta ink absorbs green light as it should but it also absorbs some blue light and a small fraction of red light as shown in Figure 10.8d. Thus, it acts as though it was contaminated with the blue absorber (yellow ink) and the red absorber (cyan ink).

Yellow ink is comparatively pure as shown in Figure 10.8f (compare Figure 10.8e). In addition to absorbing blue light as it should, it also absorbs a fraction of green light. Therefore it acts as though it was contaminated by some green absorber (magenta ink).

This will add to the color matching error. For example, if the magenta scanner measures some amount of green absorbed in the original, then knowing the green absorption of magenta ink, the amount of magenta ink required to obtain a similar green absorption can be determined. But the cyan and yellow inks also have some secondary green absorption, and if some of these inks are printed with the magenta, an excess of total absorbed green will occur in the reproduction. In a similar way other secondary absorptions will add to the color matching error.

10.6 Results

For testing the color veracity of the reproduction, the Kodak Color Control Patches shown in Figure 10.9a were used. This test chart contains both low and high saturated areas of blue, cyan, green, yellow, red, magenta, white, brown, and black. The control patches were scanned using a surface speed of the drum of 3 m/s. Kodak Wratten filters K25, K58, and K47 (cf. Figure 10.6) were used as color separation filters in the scanner head, thus detecting cyan, magenta, and blue content by the source image respectively. The input voltage in each channel was adjusted to have a maximum corresponding to the white patch and a minimum corresponding to the black patch. The one-color measurements in chapter 5 implied that there was no linearity difference between the color channels. Therefore, the same 4 x 4 exponential conversion dither threshold matrix (cf. Figure 7.2c) was used for all three channels. The resulting reproduction, shown in Figure 10.9b, was plotted on the Ink Jet Color Plotter at a low rotation speed (surface speed of 3.5 m/s).



In order to evaluate the result both the original and the reproduction of the Kodak Color Control Patches were measured through color separation filters in the densitometer (Kodak Wratten Filters K25, K58, K47). Although the measurement results may not correspond exactly to the visual sensation, the measurements are useful in tracking down the causes of an inaccurate color reproduction. Densitometer measurements on the original yield the results shown in table 10.1.

The densitometer measurements on the reproduction are shown in the form of diagrams (cf. Figures 10.10 through 10.17) where measured densities of magenta, cyan, and yellow in the reproduction are plotted versus the corresponding measured densities in the original. As only two areas, representing two saturation levels, of each color were measured, nothing can be said about intermediate saturation levels from these measurements. However, the one color measurement in chapter 5 verified that each curve approximately follows a straight line. Therefore, to visualize the color differences the two measured densities were approximated with a straight line.

10.7 Discussion of results

Subjectively most of the color patches in the reproduction correspond on the whole well with the original colors, although they did not appear as highly saturated (cf. Figure 10.9). However, some deficiencies could be detected that are a result of the non-ideal color separation filters and the non-ideal inks.

The largest deficiency is found in the black patch that appears more dark green than black. This is clearly an effect of the ink mixture which results in too much green light reflected from areas that are supposed to be black. The main reason for this result is due to the magenta ink which does not quite fulfil the tri-color requirements.

Looking at the diagram in Figure 10.17 this effect is not as clear. However, when viewing the curves in the diagram it is important to remember that the reproduction values are a result of two color separations through the same filters. First a separation through the filters in the

Measured densities of

	MAGENTA		CYAN		YELLOW	
<u>COLOR</u>	light	dark	light	dark	light	dark
Blue	0.14	1.16	0.11	0.85	0.09	0.66
Cyan	0.06	0.45	0.12	1.24	0.05	0.12
Green	0.07	0.49	0.12	1.14	0.11	0.88
Yellow	0.02	0.08	0	0.04	0.16	0.89
Red	0.20	1.09	0.04	0.10	0.36	1.0
Magenta	0.11	1.33	0	0.13	0.09	0.89
Brown	0.16	1.26	0.10	0.96	0.24	1.17
Black	0.14	1.61	0.14	1.60	0.14	1.58

Table 10.1. Results from densitometer measurements of magenta, cyan, and yellow color contents in the original Kodak Color Control Patches, shown in Figure 10.9.

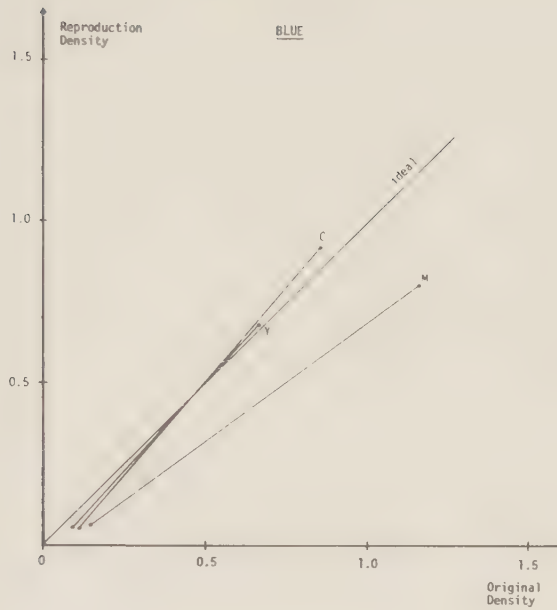


Figure 10.10. Measured densities of magenta (M), yellow (Y) and cyan (C) in the blue color patch.

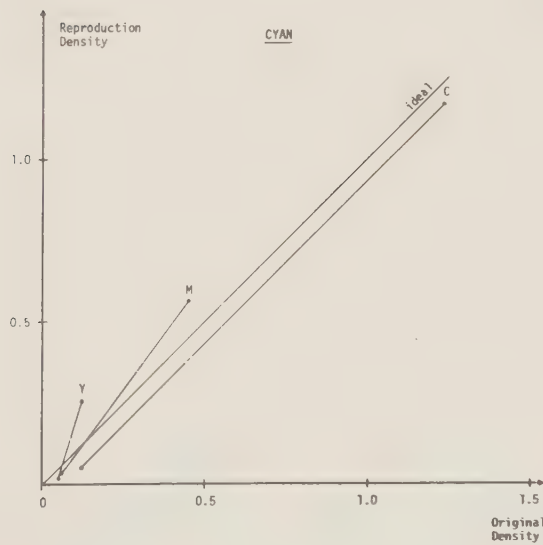


Figure 10.11. Measured densities of magenta (M), yellow (Y) and cyan (C) in the cyan color patch.

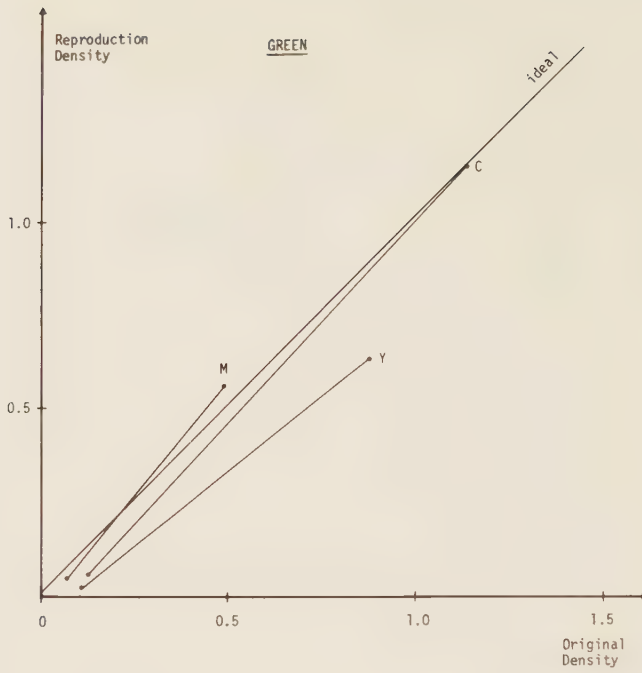


Figure 10.12. Measured densities of magenta (M), yellow (Y) and cyan (C) in the green color patch.

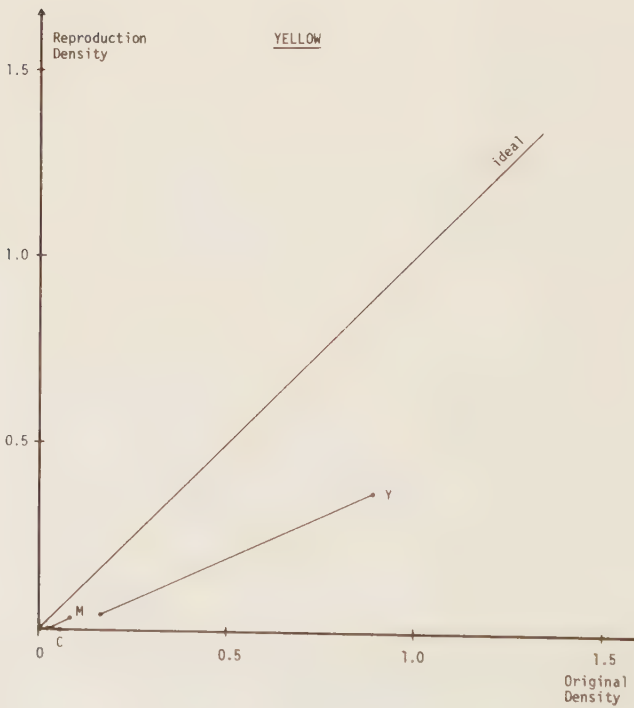


Figure 10.13. Measured densities of magenta (M), yellow (Y) and cyan (C) in the yellow color patch.

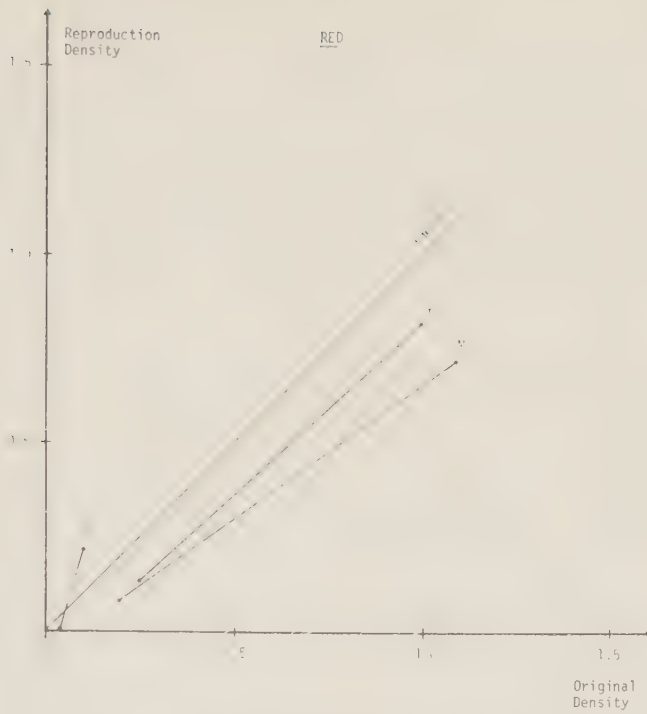


Figure 10.14. Measured densities of magenta (M), yellow (Y) and cyan (C) in the red color patch.

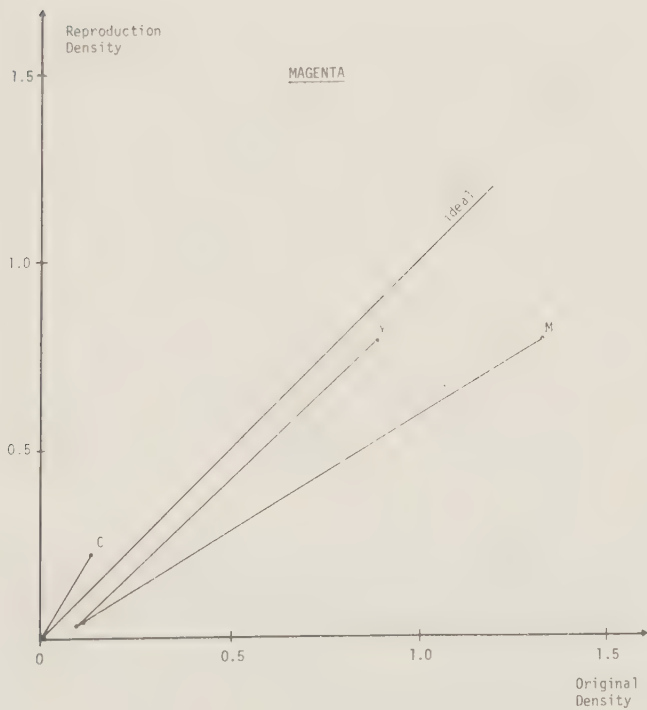


Figure 10.15. Measured densities of magenta (M), yellow (Y) and cyan (C) in the magenta color patch.

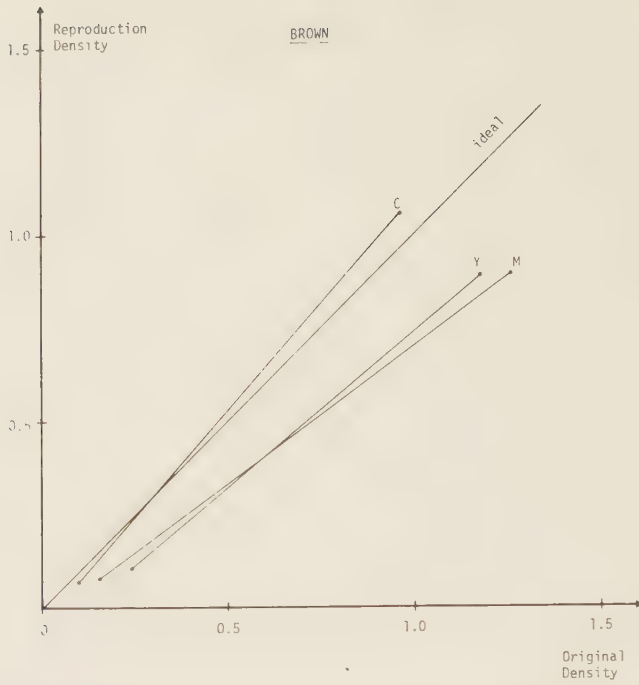


Figure 10.16. Measured densities of magenta (M), yellow (Y) and cyan (C) in the brown color patch.

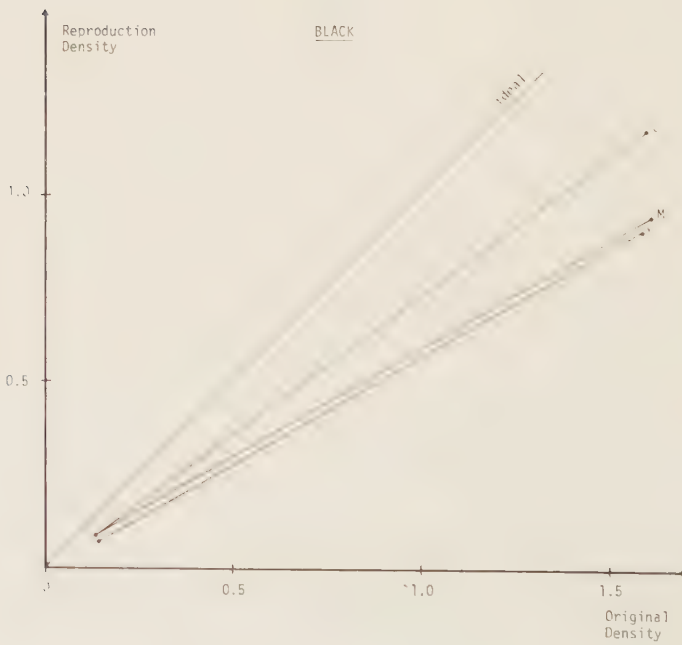


Figure 10.17. Measured densities of magenta (M), yellow (Y) and cyan (C) in the black color patch.

scanner head, then once more when the reproduction is measured using the densitometer. Thus any color errors due to the color separation filters will be exaggerated in the diagram curves. Typical examples of this effect are the yellow and magenta contents in the cyan patch, shown in Figure 10.11.

The reproduced yellow patch is almost free from color separation errors. Only a very small magenta "leakage" is visible in the diagram (cf. Figure 10.13). However, as can be seen from the reproduction in Figure 10.9b, this is clearly visible in the high saturated yellow patch, as low density levels are represented by single magenta ink dots within a matrix area. The low value of the maximum yellow density in the reproduction is due to the ink/filter combination. The absorption in the blue filter (K47) (cf. Figure 10.6) does not exactly match the spectrum of the yellow ink (cf. Figure 10.7).

The reproduction of the magenta patch clearly shows a cyan "leakage" both in Figure 10.9b and in the diagram in Figure 10.15. Even if the diagram also shows an almost perfect correspondence in the measured yellow, the measured high yellow density value in the reproduction is mostly an effect from the blue separation filter. We have already noted that "pure" yellow resulted in a low measured yellow density. So, from this and from the table 10.1 it can be concluded that whenever magenta is measured there is a conceivable "leakage" of yellow.

The blue, green, red, brown, and black patches are all reproduced using mixtures of cyan, yellow, and magenta inks. Consequently the color separation and ink problems found in the cyan, yellow, and magenta reproductions will affect all the other reproduced colors as well.

Two obvious conclusions can be drawn from the discussion above. First, better inks would result in a better reproduction of black. Secondly, to achieve a more exact correspondence between original and reproduced colors, we have to include some form of color correction. However, we have found that it is not a limiting factor in most of

our applications. In most of the applications the source image is used as a background onto which other statistical or geological data is plotted. Small errors in the color of the background information do not influence the purpose of the plot as a whole.

11 COLOR IMAGE EXAMPLES

This chapter contains two examples in color to illustrate the quality that can be achieved using the 8×8 ordered dither exponential conversion matrix (cf. Figure 9.3a) in each of the three color channels in the scanner. Both images were scanned and plotted using a drum surface speed of 3.5 m/s.

The first example is a print of a painted portrait. The original print, shown in Figure 11.1, represents a type of source images that are especially difficult to convert into a good bilevel representation using the ordered dither matrix. The source image contains much detail in low contrast regions (e.g. in the hair) and at the same time only small gray level differences that have to be detected in order to avoid large contouring effects (e.g. in the face). The result is shown in Figure 11.2. It contains almost no contouring effect, but has lost detail, especially in the low contrast regions. However, it must be mentioned that the original print contains much detail that cannot be resolved using our system (e.g. most of the cracks in the painting).

A magnified view of the reproduction from an area centered to the right of the nose is shown in Figure 11.3. This illustrates how the contributions from each color within small matrix areas are combined to yield a subjective color in the same manner as was discussed earlier in chapter 10.

The final image shows a white winter landscape. Besides showing the capabilities of the final scanner/plotter system it also serves as an early Christmas greeting from the author to the readers of this report.

Unfortunately it has to be noted that, due to printing problems, the reproductions in this report do not come out as good as the plotted ink jet originals.







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